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DEVELOPMENTS IN MANUFACTURING
PROCESS TECHNOLOGY

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43064023 Tokyo KIKAI TO KOGU in Japanese Jan 88

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Processing Methods Involved in Ceramics Processing Discussed

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[Roundtable discussion (date and place not given) by Kuniaki Umino, professor, Mechanical Department, Vocational Training Academy; Kaneshige Oma, deputy general manager, Manufacturing Department, Fujitsu Automation Co.; Yoshihiro Matsumoto, general manager, Ceramics Products Development Department, New Material Research Institute, Toso Co.; Kyosuke Ai, researcher, Machining Department, Kanagawa Prefectural Industrial Research Institute; Yasuo Tsujisato, manager, Technical Section, Diamond Machine Tool Factory, Mitsubishi Metal Corp.; Kengo Ohira, deputy manager, Technical Development Center, Makino Milling Machine Co.: "How To Advance Ceramics Processing--Status Quo and Problems"]

[Text] It is doubtless that the development and application of materials will be key technologies in the future technical evolution. Needless to say, ceramics, above all, have been watched by various industrial sectors due to their superior characteristics involving thermal, dynamic, electrical, chemical, and magnetic functions.

On the other hand, however excellent a material may be, it cannot be accepted in the form of products or parts before its processing technology has been established. Ceramics are no exception--the breakthrough in their processing mechanism, which is totally different from that of existing metals, can be said to be the leading theme in the productive processing sector at present.

During this roundtable, the discussion included problems involving materials, wheels, machines, and processing and evaluation methods for advancing ceramics processing, as well as how to advance it. (Editorial staff)

How To Respond to Material Properties and Workability of Ceramics Not Yet Explained

Umino: The two very great problems involving ceramics processing, I believe, are the cost and confirmed reliability, including surface quality. Mr Oma, will you please discuss the problems you, as a user, currently encounter in ceramics processing?

Oma: Our company uses ceramics for parts for semiconductor manufacturing devices and computer-related manufacturing devices; that is, we have begun to utilize ceramics in sectors requiring precision or ultraprecision, as the alternative to the previously-used materials, such as iron and nonferrous metals. As for the cost, processing is higher than materials. Considerable efficiency has been achieved in the roughing area, thanks to efforts made by machine tool and other tool manufacturers, with only their finish encountering problems. With regard to the quality, somewhat satisfactory results have been achieved after long-term efforts.

Umino: The problem we face is processing with high efficiency and high precision, including the quality, which naturally involves the molding and sintering of materials. Another problem involves their workability. Viewed in terms of processing, one criterion of ceramics seems to be fracture toughness values of 5 to 6. Is the development of materials targeted at viscosity?

Matsumoto: As a material manufacturer, we have racked our brains as to the kind of powder and kind of sintered body to make. The development has been advanced based on the presumable advantage of high toughness and the proximity to metals, as you mentioned. However, the greatest fracture toughness value is about 8, and for greater values, we must overcome two problems--powder and sintering. In manufacturing ceramics, we often call these two "birth" and "history," with powder and material being the former and its skillful sintering the latter. We have been making efforts to improve them, and have found it a hard nut to crack to improve the fracture toughness value.

As a material manufacturer, what we want to know, now, is what types of ceramics users want in relation to their processing. Based on our presumption that their improved strength would lead to a wider range of use, we first developed a material with extremely high strength; however, we later found that degree of high strength to be unnecessary. In this respect, we want to ask users what properties, including workability, they demand of ceramics.

Umino: Even those who work them do not know in what manner so-called grindability is connected to material properties.

Ai: We wondered if ceramics workability could be determined by their mechanical property values, and have examined some mechanical and physical property values of ceramics, such as hardness, Young's rate, fracture toughness values, the size of the crystal grain, and the crystal structure, thereby studying the relative grinding energy, life, and increased resistance values of a grinding wheel. We often hear fracture toughness values of materials mentioned in relation to their workability, but I maintain that that does not resolve the issue. What I felt interesting was that after grinding various ceramics, except for zirconia, and summarizing the results, we found that their relative grinding energy corresponded well to their elastic strain energy coefficients. We have also studied the relationship between their wear (this involves grinding ratios) and increased resistance corresponding to their life and property values, but

have found it difficult to summarize the results. It has been difficult to determine a correlation.

That is, just as alumina, as well as silicon nitride, is considerably different from piece to piece, the same is true of ceramics and, therefore, it is difficult to associate the property value of one type of ceramics with the workability of all types. We should not jump to a conclusion before examining the above relationship through exploiting various methods, such as fracture dynamics.

Umino: I agree with you. It is a serious problem that we have failed to associate the workability of ceramics with their properties. We have also conducted research involving ceramics processing, resulting in the determination that fracture toughness values of 5 to 6 are presumably one criterion. Those with fracture toughness values of below 5 tend to result in so-called crushing-type grinding, i.e., they are apt to cause intergranular fracture. When the values exceed 6, however, plastic flow is likely to occur. In this context, we presume, albeit vaguely, that the branch point of their workability exists around there. However, as Mr Ai mentioned, we find it very difficult to summarize the matter.

Next, I would like to inquire about using a diamond wheel as a tool for materials. One of the properties of diamond is its weakness against heat. High temperature hardness has been associated with this, while it also has been found that the life of a wheel tends to be longer when it is used for ceramics with low elevated-temperature strength, such as alumina and zirconia. Various diamond wheels are available, so could you give a rough explanation of, as I just mentioned, how certain wheels would suit certain ceramics?

No Perfect Wheel Available

Tsujiyato: There are various ways of classifying diamond wheels but, in general, they are largely divided by the bonds to be used--metal, resinoid or vitrified. There are, however, various resinoid bond wheels, and metal bond wheels range from those which are very porous and easy to mold to those of very high strength which use cast iron bonds.

Incidentally, I have often said that the processing of very hard materials like ceramics, unlike that of metals, involves digital chip removal. In the case of a metal, the shallower the depth of cut or the lower the indentation pressure, the smaller are the chips formed. They are analogous in form. In the case of ceramics, however, chips are either formed or not depending upon the boundary line existing in them, which may be their elevated temperature strength of fracture toughness values you mentioned just now. From our experience, in the case of materials which are extremely close, hot pressed and similar to silicon nitride in terms of ingredients, it is difficult to find the right depth of cut. Therefore, to allow chips to be formed, a wheel must be fixed or rigid, since the ceramics are hard enough to withstand cutting. They differ from metals in this respect and it is believed in principle that, for chips to be formed, a vitrified, ceramic, or metal bond wheel is superior.

Incidentally, apart from this, the problem exists involving retaining the wheel's cutting ability--sustainability as well as cutting ability. When it comes to sustainability, various data shows that a resinoid bond wheel, weak in holding force and abrasive grains, tends to display relatively more prolonged cutting ability since it allows the smooth change of cutting edges, although under ordinary surface cutting conditions, which indicates a contradiction in wheel selection. In fact, in the case of the surface cutting of silicon nitride with a machine having low rigidity of about $1 \text{ kg}/\mu\text{m}$, the intended results will not be achieved unless a resinoid bond wheel is used, I think. However, in other cases, I think a rigid wheel can play a more active role, while a metal bond is more profitable economically. It is so low in cost that we want to cut not only ceramics, but everything else in addition with a metal bond wheel when we consider cost. At the moment, however, we are sorry to say no perfect wheel is available which is capable of cutting all ceramics at low cost.

Some unique wheels are available. We have manufactured thin-edged cutting wheels with extreme hardness and providing high precision. They are suitable for cutting and fluting ceramics, since they are hard and stable in shape, while they require dressing as their hardness prevents them from providing autogenous regeneration. As you may know, no one wheel can be mounted on any machine to cut any ceramics, but there may be one available which can be widely utilized with the help of peripheral software and systems.

Umino: I think we are largely indebted to grinding wheel manufacturers that efficient processing has become possible, which means that individual manufacturers have made excellent wheels. From the users' standpoint, however, the problem exists involving knowing which wheels to use. Know-how, including wheel selection, has not been widely available for users, while manufacturers should tackle the problem of developing software for that. What vision do you have regarding the development of wheels?

Tsujisato: A considerable number of small businesses are processing ceramics, while it seems that field workers are not well informed about ceramics. When they handle ceramics, some say, "This material is rather white, and I find white ones somehow easier to process," which illustrates the fact that ceramics are not well known to them as a material. Of course, they have studied the material and have sufficient knowledge regarding it in some fields.

In any respect, you must know what you are processing. One point in processing is to find a wheel appropriate for a certain material with a given property value. At the moment, this has not been identified yet, but a rough idea can be gained by its Mohr's value. In many cases, the information needed to compute Mohr's values is not available at the end processing fields. Without it, we cannot offer wheels corresponding to the materials to be processed. Therefore, the first thing we must know in developing a wheel is what material it is to be used for. Next comes what type of wheel to develop, and I am very attracted by metal bond wheels. In any event, our final target is, I think, one which is hard and can be

manufactured at low cost. However, its disadvantages include the fact that its cutting ability fails to be retained since it is shaped with difficulty, so that it needs to be returned to its manufacturer for correction every time it becomes necessary. If these defects can be offset by means of relevant software and systems, this wheel is very likely to be used more widely as a very excellent choice. Its further R&D should, therefore, be directed toward this goal. With regard to vitrified-bond diamond wheels, too, further research seems to be required. Processing a hard, brittle work material with a resinoid bond wheel permits a satisfactory surface roughness to be obtained, although regrettably it results in an edge slack of a micron or fractions thereof due to its elasticity. Dealing with materials which require extreme sharpness and flatness is an issue, and, for a long time, we have ground precious stones with ceramic wheels. Therefore, we think a vitrified-bond diamond wheel or ceramic-bond wheel would be quite effective for these materials, too. It is inferior to a metal-bond one in ultimate durability, but I think further study should be made regarding its higher precision. Research on the vitrified bond in respect to CBN has advanced considerably, however, research on it regarding diamond wheels should also be furthered for use in processing ceramics.

Umino: When it comes to selecting wheels for purposes of efficiency, for example, it boils down to those providing good depth of cutting by abrasive grains or rigid ones, such as those using metal bonds, while for improved quality, it is reduced to elastic ones, such as those using resinoid bonds. When a car runs along an expressway, the tire is better at a higher level, while along a gravel road a lower level is preferable. This also applies to wheels in that they need to be changed according to the target of the grinding operation. When it is aimed at expressway driving, that is, at improving efficiency, a wheel with high air pressure, like that found in a metal bond, is effective. This is a wheel with a short arc of contact which causes it to cut too deeply, thereby tending to result in poor surface quality. On the other hand, a resinoid bond wheel is one with low air pressure and a long arc of contact. A long arc of contact means multiple simultaneous cutting edges and less load per edge, which may cause the surface slip of a wheel, but results in good quality of the processed surface. Therefore, you can use a metal body wheel for improved efficiency and a resinoid bond one for improved quality, but trying to improve efficiency leads to poor quality and vice versa. I would presume that a material has its own optimum air pressure or an optimum wheel for processing. What do you think of this idea?

Tsujisato: We have all heard the term hybrid or metal resin, and such an approach is being made by us as wheel manufacturers. In the case of resinoid bond wheels, some contain fillers and filling materials, as well as resin and abrasive materials. Fillers include various materials, one of which is metal, such as copper, copper-tin, and cobalt. When they are applied, it is difficult for a wheel to become a soft metal bond one. We can call it an intermediate one, between one with high air pressure and one with low air pressure, therefore, it is possible to control the air pressure of a wheel for specified materials.

Umino: Then, do you think there will be an ideal wheel?

Tsujisato: No, I do not think there is an absolutely guaranteed wheel and bond.... Because we cannot find one, even among general wheels with their long history. I think, as I mentioned before, this ideal will be realized with the help of some system or software.

How To Control Wheel's Surface

Umino: When it comes to software, the greatest problems involve dressing and truing, and when I visit small businesses, I often feel they have been done halfway. What do you think of this?

Ai: I think both truing and dressing are different in the way they are used for one-line production than for mass production. It is all right for one-line production, however, in the case of mass production, we are sometimes bothered by the immediate wear of truing tools. Individual manufacturers have offered them in different forms, but I am sure no overall truing and dressing methods are available at the moment, therefore, we select proper methods on a case-by-case basis. This is the case. You mentioned metal bonds before. We also conducted truing and dressing for FC and metal bonds with a truer using a GC grinding wheel, and found them to be very difficult. A method exists in which electric discharge machining is used for truing and dressing, which seems very difficult to apply at general firms.

So, the next problem involves the types of wheels that will ease the truing and dressing process. When it comes to ease of truing and dressing, the best candidates are vitrified and resinoid bonds. In truing and dressing, the conventional stick cutting method seems to be used in general. However, it apparently is not yet understood how much truing and dressing needs to be conducted in order to achieve the intended wheel surface. Therefore, I think it is necessary for relevant information to be summarized and provided. With regard to truing and dressing devices, we have test manufactured and operated a truer using a diamond tool, which has proven to be very good. While manufacturers have put characteristic truers on the market, they seem to have found few applications due to their high prices and difficulty in handling.

Umino: Since control of the wheel surface is generally left to field workers, how do they do it in your company, Mr Oma?

Oma: You mentioned controlling the wheel surface through the resistance you sense when you handle it. We do it using a magnifier for visual observation. We check the wheel surface before and after dressing. Field workers can judge the completion of dressing upon the sight of bright diamond scattering.

Tsujisato: The wheel surface can also be controlled by providing a simple device for the machine, in which a dressing stick is pressed periodically. The interval is found by the empirical value, and the stick is pressed based on this, say, once per hundred pieces, or once every several hours.

One machine, I mean a grinding machine for diamond compact tools, requires constant pressing. It is used to grind diamond with diamond, so that without doing so, it will be incapable of immediate cutting. In other cases, however, you do not have to do so since diamond will wear remarkably. So, you need to find the proper interval for pressing the stick. This can be done in the field, although it is rather difficult.

Umino: One of the recent decisive factors in the fields has been the introduction of NC (numerical control) and automation and, with regard to dressing interval control, have such methods been introduced into the fields as measuring using a sensor, for example, cutting resistance and dressing the wheel when it increases, or measuring using AE sensor frequencies and dressing the wheel when a specific one is detected?

Ai: Dressing life or, in other words, a digitizing wheel life in some form and feeding it back--such a method is rarely used, I think, with ultra-abrasive grain wheels, such as diamond and CBN wheels. A method using an AE sensor is certainly available, but in reality, no fields I know of have introduced it. In many cases, it seems that they stop processing when they judge the wheel to be incapable of grinding by sensing the roughness of the processed surface or axial deflection.

Umino: Ceramics processing is involved in producing important parts. Therefore, it is forbidden to destruct workpieces. However, processing a workpiece with a dull wheel may break it due to various reasons, such as the lost balance of thermal shock, vibration, and residual stress. So, I think control of wheel dressing is crucial, but how is it that, as you mentioned, automation can be used in dressing, such as a sensor, for that does not seem to be widely practiced?

Tsujisato: The words "ceramics processing" give me an image of processing small workpieces. In the case of small lots of small workpieces, a wheel is changed or adjusted at the completion of each lot. In the case of mass-produced workpieces, in the fields first they try to find the proper intervals, including factors of safety for dressing, rather than throwing money into such equipment as providing a sensor of adaptive control function for the machine, I believe.

Umino: Then, it is a matter of size and the return on the investment.

Tsujisato: We have problems with large workpieces. In some cases, you cannot change wheels during the processing of a workpiece for some length, say, from here to this portion, and how to deal with this is a problem, to be sure. In the case of small workpieces, however, you can respond to it the way they do in the field.

Integral Use of Machines and Wheels

Umino: Makino Milling Machine Co. has participated in the R&D of ceramics processing, as a machine tool manufacturer, in combining a machining center and a cast iron bond wheel, but could you tell us about your basic approach?

Ohira: The processing of completely sintered ceramics is possible only through grinding, but grinding in this case, I think, has a different objective from that of conventional materials. So far, grinding has been conducted in pursuit of a high grade surface or for the processing of workpieces which can be made only through grinding, however, in the case of ceramics, I think that highly efficient processing, as is the case with metals, to say the least, is required. Incidentally, ceramics are involved in multiple small-lot production. Also, our basic attitude is to respond to such needs as grinding workpieces of multiple small-lot production with high efficiency.

Furthermore, the processing requires the integration of the machine and wheel and expertise in their use. So far, R&D of these three has been conducted separately--machines by machine manufacturers, wheels by wheel manufacturers, and instructions for their use by users, but this never leads to highly efficient grinding. In this context, we intend to establish technology involving not only machines, but also appropriate wheels for them and how to use them. However, our company is not a grinding machine manufacturer. We have been approaching grinding as a cutting machine manufacturer would, that is, we have been studying the possibility of applying expanded cutting functions to grinding. We think that wheels likely to be appropriate for such grinding will be, as Mr Tsujisato mentioned before, strong, tough metal bonded ones. In fact, ceramics grinding with this kind of wheel has reached the metal processing level. What you find necessary in using such wheels are truing and dressing, and we have developed truing technology, using electric discharge processing, that is adaptable for metal bond wheels. We believe that high grade processing with very high efficiency has materialized through combining them. With regard to truing cycles for cast iron bond wheels, it is impossible to quantify them for different types of grinding, but wheels can be used for quite long periods on a practical basis. As for their automation, the company is a machine manufacturer and somewhat good at it--so we have almost completed it.

Umino: Grinding jobs using a machining center results in the low peripheral velocity of a wheel. The low peripheral velocity causes the wheel grade to soften and vice versa. In this sense, a cast iron bond wheel with strong holding force should be appropriate for a machining center, I think. Removing the most possible machining allowance is desirable for temporary sintered materials, and in this case, a cast iron bond wheel would be shaped like an end mill. Incidentally, what do you want for ceramics processing machines from the user's standpoint?

Oma: For a relatively long time we have been studying a grinding machine for use in the final process of ceramics processing, in cooperation with its manufacturers, and the main priority seems to be axial rigidity. Our work involves processing for fine configurations, such as flute processing, and with a horizontal-spindle grinding machine, axial rigidity, including the spindle's column deformation, of at least $10\text{-}15 \text{ kg}/\mu$ is necessary. Its dimensional follow-up ability must be $0.1 \mu\text{m}$, with $0.2 \mu\text{m}$ at the worst. Also, it needs to have cleared thermal deformation and have stability in

sliding. Then, one more request is that it needs to be mechanically capable of both creep feed and stroke grinding for both grinding and rough wheel finishing.

Umino: Are there any machines currently available that can meet the demand?

Oma: We have asked several manufacturers to develop and simulate such machines, and we have found that some of them are likely to meet our demands, although we have yet to make the final evaluation.

Cost--The Final Problem

Umino: You mentioned just now great rigidity and I understand that the ideal bearing requires high rigidity and excellent rotational accuracy. What type of bearing do you think is most likely to be targeted from among the various types, such as antifriction bearings, air bearings, fluid bearings, and magnetic bearings.

Oma: The ball (antifriction bearing) is the highest in rigidity, but we are thinking of using oil for smooth grinding.

Umino: How much rotational accuracy do you think is necessary for the main shaft?

Oma: Well, an accuracy of about $0.3 \mu\text{m}$ is required for practical use. We have had a great number of requests as mentioned, however, the primary problem is cost. Machine manufacturers prepare detailed designs in response to our requests and conduct simulations as the final evaluation stage, but it is the cost of manufacturing the machine that counts. This problem always prevents us from making any decisions.

Umino: Mr Ohira, I understand your company is not a grinding machine manufacturer but I think your machining center I mentioned before is quite high in cost, when compared with the conventional ones used for metal processing. Is this so due to the current small scale?

Ohira: No. Ours actually are not that outstandingly high due to their ceramics processing ability. Of course, they do provide extra functions, such as increased revolutions, when compared with conventional ones, and those we have aimed for can be manufactured without changing the conventional forms very much, so they are not as high in cost as newly-designed ones.

Umino: The initial cost is, however, still a big problem for small businesses, which is also true of material manufacturers.

Matsumoto: I belong to the research institute at present and I do not need to worry much about the matter, however, from the manufacturers' standpoint, I believe a significant problem lies in how soon you can depreciate your machines and facilities.

Umino: After all, the absence of mass production results in the problem involving initial cost, I think.

Matsumoto: Among engineering ceramics, only alumina has been successful, while the others have not been used very much. They are not used due to their high cost, and their manufacturing cost becomes high since they are not used. We are experiencing quite a dilemma. That is why we always hear, "They have excellent properties, but their cost...."

Total Approach Necessary for Ultraprecision Processing

Umino: Mr Oma mentioned just now that, apart from cost, some machines are beginning to meet users' needs to some extent, but when their main shaft's increased rotational accuracy and fine cutting permit the fracture unit to be small, do you think a wheel different from conventional ones in form, such as an atomized one, is likely to appear with diamond wheels, too?

Tsujiato: I do not think there will be a great difference in basic form. With regard to the grain size of abrasive grains, one offering $1/8 \mu\text{m}$ is available at present, which is used for grinding record needles, and a wheel using such grains as powder can be made in principle. However, the problem arises regarding whether it is possible to make a worthwhile high-precision wheel using grains not as fine but, for example, of $1 \mu\text{m}$. Higher orders of wheel concentricity and balancing must be provided, and if ultraprecision in the true sense of the word is aimed for, it is not enough to merely make abrasive grains fine. We need to consider dynamic balancing on the machine with deflection of the shaft and all included, that is, as I mentioned before, in association with the total system.

Oma: I agree with you. Dynamic balancing will become very important, so we want grinding machine manufacturers to take that into full consideration.

Umino: When we think of causing fractures within grains, the crystal grain size (zirconia is small and alumina is large) of a material presumably affects its workability. What is your opinion?

Oma: It is difficult to discuss the quantitative relationship between a material grain size and its workability, however, cracks cause problems in alumina processing. The use of zirconia as a binder to eliminate them apparently results in very good surface condition. But, zirconia causes the grinding resistance to increase, so the surface becomes good, while the efficiency becomes poor. This presents a dilemma.

Umino: In other words, small fracture toughness values require a small amount of processing energy, but tend to cause cracks. Therefore, the use of zirconia, which is prone to cause plastic flow, increases the grinding resistance.

Matsumoto: Let us go back to our first subject--what mechanical properties of a work material affect its workability. Mr Ai said that without

zirconia, a material's coefficient of elastic strain energy corresponds to its workability.

Ai: Yes. I am confident that we have conducted a relatively strict experiment involving the matter, and I think further research will make it clearer. I believe fracture toughness values are obtained by reading the crack length through the Vickers impression. Reading is, however, not always easy, depending upon the materials, and I think a simpler method will permit better judgment.

Umino: That is a matter to be boiled down by material manufacturers and processing businesses. Comparing it to the academic level, it is as if the Ceramic Association and the Precision Engineering Society would have to research the matter in cooperation...(laughter) And, can you say that there is a difference in machines between those required for ultraprecision processing of materials like alumina, with small fracture toughness values and vulnerable to cracks, and those for processing materials like zirconia with large fracture toughness values and behavior relatively similar to that of metals?

Oma: I would like to agree with Mr Umino's comments.

Umino: Is it also true of wheels?

Tsujiisato: As I said before, it is true that no perfect wheel is available. Those used for processing alumina have different properties than those for processing zirconia. For example, once we conducted an experiment, using a resinoid bond wheel, involving the influence different abrasive grains have on processing. We used three types of General Electric Co.'s diamond abrasive grains--those with excellent crushing ability, standard ones, and relatively tough ones. The experiment proved that for materials like alumina, wheels with tough abrasive grains can last a long time, but processing silicon nitride or zirconia results in a large number of grains falling, so that for materials with large fracture toughness values and tough ones, it would be rather better to use micrograin-like abrasive grains with rather good crushing ability from the standpoint of the grain's autogeny within the grain boundaries or microchipping.

Umino: It is necessary to maintain a good combination of a wheel, machine, and their use, which involves the matter of abrasive grains. Incidentally, along with improved rotational accuracy and microcutting accuracy, the uniform ejection height of grains becomes crucial. Do you have any advice from the standpoint of the field?

Ai: Making the grain height uniform is associated with the measuring method, I think, and a simple method we use involves grinding a thin piece of soft steel with a diamond wheel, measuring its surface with a roughness meter, and checking its configuration and section curve. In this way, you can make a perceptible judgment of its conditions, good or rough, with relative ease. We also never fail to check wheels this way during our experiments.

Umino: When I visit small businesses in the field I find few of them conducting truing and dressing operations so carefully as to repeat them. I am sure remarkable results would be achieved by doing so.

Tsujisato: I agree with you. The higher the accuracy we pursue, the more necessary this will be, I think. From our experience too, when we deal with a large amount of truing, we find the diamond wheel very dull, with no ejection of abrasive grains on the wheel surface. In this case, the truer also fails to cut well, and if you keep truing without considering that, it will cause a load to form on the wheel shaft. So, in this case, dressing should be made first if truing is not completed, and then truing can be resumed.

Important Problems Involving Grinding Fluid and Powder Treatment

Umino: Some reasons for poor ceramics processing include poor control of dressing, as I mentioned before, and ill-matched machines with wheels; few small businesses have machines for ceramics processing and they often use conventional grinding machines designed for metal processing. Another reason involves the problem of dynamic balancing that Mr Oma mentioned before. In addition to these, the grinding liquid is involved. Actually, the grinding liquid seems to be poorly applied in many cases, but is it necessary to change how the grinding liquid is applied from that used with conventional metals?

Tsujisato: It can be said that in ceramics processing, proper application of the grinding liquid can be very effective. A comparison of grinding ceramics and metals with a diamond wheel (cemented carbide was used since diamond is said to be ill-matched to ferro-metals) shows a considerable difference in their optimum peripheral velocity. In the case of ceramics, comparably fast grinding permits good efficiency and prolonged life, while with cemented carbide, the optimum values of the wheel's peripheral velocity are 1,500-1,800 m/min in formal wet grinding. Slower grinding causes the wheel to act softly, as you mentioned before, while faster grinding causes the wheel to wear, since development is vulnerable to heat. On the other hand, viscous materials, like cemented carbide, have large resistance values, so that in grinding they require a large amount of energy and produce heat, although geometrically, the higher the peripheral velocity, the longer the life of a wheel. This is why the wheel's peripheral velocity cannot exceed these values. In the case of ceramics, even the optimum area of the peripheral velocity of very tough silicon nitride, however, is higher than that of cemented carbide. It is characteristic of processing to form crushed chips away from the plastic flow area, isn't it? The point is to cause cracks. I presume, therefore, grinding ceramics at considerably high velocity will produce less heat than grinding cemented carbide. Nevertheless, since development is vulnerable to heat and a great number of wheels seem to use resinoid bonds, when the grinding fluid is poorly applied so that it becomes half dry, the wheel often becomes dull, resulting in poor efficiency. In the case of hard, brittle materials, a considerable difference exists in the grinding effects produced by one type of grinding liquid over another, or by one close to

oil over one close to water. They used to use kerosene and the like for processing crystal. I believe this proves that a grinding liquid rich in oil is effective for hard, brittle materials.

Umino: Our data shows that a liquid containing fats and oils and capable of preventing coagulation would be better for oxides, because they cause blinding with water, and would presumably do well for silicon carbide and the like. At any rate, we must pay attention to how we apply grinding liquid and what type is used.

Ai: We often receive inquiries regarding the primary performance of grinding liquids and its treatment. As for the primary performance, we conduct normal grinding and creep grinding of ceramics, but we do not compare soluble ones and emulsion, so it has not been explained yet. However, we use mostly water system fluids in creep grinding, especially chemical types, since quite high pressure must be applied during it, and the chemical type eliminates the problems found with sticky oil. With regard to its treatment, inquiries have been made by many firms. We feel that in selecting a grinding liquid, we should consider not only its primary performance but also its ease of filtration and after-treatment or its performance as a whole. It is difficult to use emulsion for our centrifugal treatment involving applying a filter and, therefore, prefer the chemical type.

Umino: At my university, we are studying what to do with ceramics powder separated by paper filters. In the case of a machining center, too, we fear that powder will come onto its sliding surface. What about this?

Ohira: We are paying considerable attention to this as a function to be added to a machining center. The grinding liquid has been mentioned before, and we use a larger amount of it for grinding than for cutting. The grain size of ceramics powder contained here is below 1 μm , which is stirred up in a misty state. Then, problems involving the above-mentioned sliding surface and spindle arise. We prevent liquids from flowing up to the sliding surface. In addition, double or triple measures are taken, such as a special wiping of the sliding surface itself. An air seal is also made for the spindle, that is, the spindle's inside pressure is kept high to prevent the ceramics powder contained in the mist from entering it. These methods seem to be very effective, since our periodic check of machine accuracy involved in grinding ceramics for the past 2 years shows no changes.

Umino: Mr Oma, do you take any measures for the grinding liquid treatment?

Oma: Well, we mainly use paper filters. No other simple ones are currently available.

Breakthrough in Processing Mechanism Necessary for Development of Combined Processing

Umino: Ceramics processing includes, in addition to grinding, the approach of so-called combined processing. What about its efficiency?

Ai: We also have been advancing research involving supersonic grinding. A core drill using a supersonic spindle is very effective for drilling, while we have conducted an experiment to determine its efficiency in grinding planes or end faces with supersonic waves added to workpieces. As a result, through evaluations of various aspects, such as resistance, finished surface, residual stress, etc., we have found that the addition of supersonic waves to workpieces does not seem to be very effective in normal grinding. A supersonic wave does not seem to work well in cutting a plane engaged in linear contact. Next, we cut a plane with a cup-shaped wheel, and have found that cutting workpieces with a supersonic wave added to them has resulted in a relatively good job through normal grinding, as a machine low in rigidity often causes slack end faces of workpieces. Therefore, I think it is necessary to consider the processing method to be used when a supersonic wave is added to workpieces.

Umino: A study of the number of simultaneous cutting edges when a supersonic wave is added to a workpiece shows that the quantity of wear per cutting edge is very small with large wheels. On the other hand, wheels for internal grinding with fewer cutting edges force every abrasive grain to work more, and by providing a "beat" with supersonic wave in this case, we can expect the autogeny of abrasive grains. From this, we may say that a supersonic wave is effective not for every area, but for limited ones. I think this is true of other combined processing methods. The supersonic wave is sometimes referred to as all-powerful, but is actually effective only within a limited range. We also have been conducting research on supersonic grinding and have found that the method involving adding a supersonic wave is appropriate for coring of 6 mm or below, or internal grinding, but other methods would be better for other cases.

Tsujisato: We have conducted previous experiments involving supersonic grinding. We thought applying a supersonic wave toward the wheel shaft would limit the wheel size. We also wondered if we could shake the wheel where it holds a workpiece since, in our production field, grinding is conducted by pressing small disposable tips onto a large wheel with an outside diameter of about 300 mm. Experiments were then conducted, proving the shake effective. They were conducted by two methods--applying a supersonic wave with an amplitude of about 20 μm in the pressing direction and one at a right angle to the pressing direction, or parallel to the wheel surface, both resulting in remarkably good processing efficiency. An anticipated problem in the practical use of this method using a supersonic wave would be that the necessity of providing proper supersonic waves according to the workpiece size, specific gravity and materials would require changing shafts. Some agreeable method may be devised for this, and its possible solution presumably would lead to the practical use of this method to some extent.

Umino: I think control technology can respond well to the matter if the workpiece is limited to some extent, for example, using disposable tips. However, combined processing, not limited to that using a supersonic wave, is likely to advance if the following is made clear: What effect a supersonic wave has, how a supersonic wave acts to be effective, and

whether its effectiveness is due to autogenetic action by its "beat" or by its preventing a filter from blinding.

Ohira: Practically, in supersonic processing, we can never avoid such problems, as you mentioned, as changing tool lengths in order to obtain a supersonic wave suitable for the work. Then, we wonder if the supersonic wave is all right or if we cannot expect an oscillation with a lower frequency to be that effective. So, there is potential for the development of this type of combined processing. At the moment, research into supersonic processing is thriving because a supersonic wave is relatively easy to obtain.

Umino: The importance of dynamic balancing was mentioned before. Then, how about this? You force balancing to be lost on purpose to cause a "beat," expecting autogenetic action, thereby permitting perfect balancing upon finishing. If you can use control technology successfully and control it, I think combined processing in some other form is likely. (Laughter) We are divided in many ways regarding the evaluation of electrolytic discharge, which must mean that it may, or may not, be suitable depending upon the type of grinding, as is the case with supersonic processing.

Ai: I heard that a certain company, which had introduced an electrolytic discharge processing machine, was successful in processing one material with it although the material's properties were not explained. If this is explained, we can gain a clue to determine what materials are appropriate for this processing method, thereby permitting it to advance further technically.

Umino: I understand some materials are appropriate for combined processing and others are not, which must be made clear in cooperation with material manufacturers and processing businesses.

Matsumoto: That is important, to be sure. Material manufacturers, including our company, are currently conducting experiments to determine what materials are really suitable for that process. The processing of silicon nitride, for example, includes reaction sintering and hot pressing, and it displays varying properties according to the quantity and composition of its assistants. It is currently in a chaotic state, but I think the right direction will be roughly decided some time hence.

Bottleneck When Ceramics Adopted for Machine Parts

Umino: Inquiries are often made about threading ceramics or the processing of deep holes with small diameters, and I think we need to consider them comprehensively, including using other processing methods. Processing one part includes various processing methods, such as tapping, therefore, we must take a second look at processing from an elementary standpoint. Then, we come to face even such problems as whether the included angle really has to be 60 degrees when ceramics parts are used, so a design approach permitting ease of processing should be presented by the machine side.

Matsumoto: A design unique to ceramics is necessary, of course. Whether processing greenware or that temporarily sintered, we sometimes need, for example, to take R as it forms 90 degrees, a portion where cracks are likely to occur, so it is certainly necessary to design ceramics parts giving full consideration to ease of manufacturing and their material properties. We have not advanced that far, that is true.

Umino: Mr Oma, I understand your company actually designs ceramics. In designing ceramics, say, for example, you want some portion of an object to be joined differently for ease of processing, but find it difficult, so you change its design in some other way. Does this happen sometimes?

Oma: Well, we really do that. For the key portion, we put a metal bush into the ceramics and thread it. Therefore, a key point here is the adhesive performance of ceramics and metal. We want to thread ceramics themselves, but we are worried about their shock resistance.

Matsumoto: I think we do not have to worry about it per surface, but per point, stress may concentrate and cause cracks to expand. We can, however, thread ceramics when they are green, taking into consideration their shrinkage percentage, so we can fit a set screw well for the ceramics' external thread, although it is not clear how great a force it can withstand.

Umino: We really require more design and processing technologies to that extent.

Ohira: We manufacture discharge processing machines, and once we found it necessary to use ceramics to make parts, which had conventionally been made of stainless materials to improve their performance. We conducted a number of trials, one of which was on the thread you mentioned just now. We tried with greenware, which turned out to be practically in vain. We tried to use screws of M 4-6 made by some other company to go into pure ceramics threaded by a supersonic wave, however, a problem arose involving their stability and, in the end, we changed the design to one using a bush. Initially, we did not have enough time and tried, in vain, to use, as it was, a design made for metals for ceramics. In the end, we changed the design as needed, with the result that we could reduce the cost so much that it could be incorporated into our products. At present, we actually do use ceramics parts. Use of ceramics for machine parts, however, still poses problems to be solved in the future involving deep holes with small diameters and screws. The problem will naturally arise that a hole's diameter is too small for a bush to go through which, I think will be the greatest bottleneck occurring when adopting ceramics for machine parts.

Awaited Establishment of Assurance Technology

Umino: As I mentioned at the beginning of this roundtable discussion, I think we need to consider, in addition to efficiency, reliability, and the fewest possible cracks on the surface from various aspects, such as materials and machines, but also, is there any good method available by which field workers can find surface cracks?

Oma: The simplest way in the field is a penetration monitoring method, I should say, where you brush Magic ink [a kind of marking ink] over the surface, wipe it off immediately, and check for any remaining ink. We use this method and find cracks as large as 20 μm . They are found after rough grinding, and then removed later.

Umino: What final crack area would be desirable?

Oma: Less than 1 μm , I would say.

Umino: Then, lapping in the end?

Oma: Yes.

Matsumoto: You are talking about cracks caused by processing, however, materials present the problem involving pores and we are trying to eliminate them as much as possible, but we have not been able to establish assurance technology. The pore size of metal withstandable to fracture seems to be some fraction of a millimeter, while with ceramics, the closer to the surface, the more strictly we need to find pores of below some tens of μm due to stress expansion, etc. Methods using a supersonic wave or soft X-ray are available but the case is that no companies have established assurance technology yet.

Umino: The reasons for that may be due to the diverse materials and detection ability, however, it will pose a substantial problem in the future from a practical standpoint for such frontier industries as those involving computers and aerospace, which require additional precision. As you mentioned just now, we need to eliminate cracks caused by processing and those contained by the material itself to enable practical use.

Oma: So, there is a considerably strong demand for the nondestructive inspection of new materials.

Umino: It seems like I am going back to the beginning, but I think ceramics processing will find it difficult to adapt to future industries without balancing, what you mentioned just now included, the material, wheels, machines, and processing conditions. What potential do you see regarding the matter?

Matsumoto: Apart from materials, we are experimenting with nondestructive inspections in many ways for quality assurance of the materials themselves. Since we cannot conduct the inspection ourselves, we take various materials to inspection equipment manufacturers to test, with no satisfactory results achieved yet.

Umino: We often hear processing companies complain that they cannot readily apply data offered by the Academy as data on materials by material manufacturers since such data as that involving a sintering state is not available. Is there any movement afoot to study the matter in the industry? If not, the debate cannot lead anywhere.

Matsumoto: I agree with you. There is movement to collect various databases in the "Fine Ceramics Center" in Nagoya, so it will be available there. It is surely necessary that the processing and the material sides complement each other.

Umino: Then, as a whole, it seems we come to the conclusion that the matter cannot be solved without the cooperation from material, machine and wheel manufacturers, and users.

Oma: I can understand very well that we have to do so, but new materials represented by ceramics are used for specific purposes. Their use is largely related to corporate secrets, so it is difficult to have their complete functions explained.

Umino: Ceramics processing needs to be made by allowing a machine, material, wheel, and their respective uses to complement each other. However, when the corporate side points out the above-mentioned difficulty, I think such processing can be accomplished by public organs, such as industrial research institutes or universities. The cooperation of industries, academia, and the government must be promoted centered around public organs. Do you think it likely that such research arrangements will come into being?

Ai: Mr Umino says that businesses are being asked to offer their data, and research arrangements are being made through the cooperation of industries, academia, and the government centered around public organs. But, I think this will be difficult since it involves corporate secrets. Local public research institutes, however, sometimes do use collaboration by this trio effectively to solve specific technical themes common to small businesses within their areas, with the technical R&D expenses contributed by these businesses. In Kanagawa Prefecture, a project involving new ceramics application technology development has been underway since FY 1985 on a 3-year program with the trio's cooperation. It seems that research by this trio is conducted often, as is the case with the above-mentioned project, when the impact on small businesses is involved.

Umino: Then, do you mean, for example, that when small businesses have a problem involving their research, industrial research institutes recommend that they conduct such and such research?

Ai: No arrangements have not been made well enough for them to be able to say that confidently. There may be discussions, however, between the two parties about what form the research should take in the future or in which direction it should advance.

Umino: I think, however, it is necessary to reorganize some institutes to enable them to receive and solve problems submitted by industries involving further expanded application for ceramics. When it is difficult for businesses to disclose their data due to corporate secrets, I think it necessary that public organs summarize such data or assist them. By the way, material manufacturers, for their part, may sometimes want data

involving wheels or machines, but it is difficult for one company to collect this information. How are they going to solve this?

Matsumoto: Data on many subjects can be obtained by participating in associations led by, for example, the "Ceramics Processing Research Association." On the other hand, when a request is made by a wheel manufacturer, it can be in the form of collaboration of workability with samples offered by the relevant association.

Umino: That means they want a place at which to exchange data, that is, can we say the currently available data is not sufficient?

Matsumoto: You are right.

Umino: Mr Tsujisato, I hear your company offers data for payment. What is it like?

Tsujisato: Yes, we have practiced this for 3 years. Basically, it is based on the grinding experiments we conducted using a wheel manufacturer's research equipment. Specifically, when we get a request from a user for data involving grinding of this material, we offer data obtained by the current experimental results, past ones, and the relevant literature. Actually, however, businesses already involved in ceramics processing have far more data than we do on each material and its processing method. We collect data on a wide and shallow basis, therefore, our information service is targeted at businesses processing ceramics for the first time.

Umino: The point is that where the required information, available to users, can be found should be made clear. This can be done by research institutes, universities or the private sector.

Ohira: It can be said that under the current circumstances in Japan, we are all desperately trying to make something new or have higher added values; therefore, it is crucial that, in the future, Japan solve the problem involving integrating relevant processing technologies as a whole and systematizing them, isn't it?

Umino: I agree with you. We are facing very great problems, including research arrangements, and, therefore, we must try to solve the matter through discussions among various sectors. We currently lack places at which information exchanges can take place, but we have prospects for the future. A great number of problems lie ahead, however, I think we can solve, if not all, some of them through the cooperation of industries, academia, and the government.

Profiles of Attendees

Professor Kuniaki Umino: After graduating from Vocational Training College in 1968, he continued his research, focusing on grinding, at the same college, and was appointed professor in the Mechanical Department in October 1987. He was awarded the Precision Engineering Society's Aoki Commemorative Monograph Prize in 1978 for his "Selective Criteria for

Grinding Wheels." His view is that, in order for fine ceramics to be widespread on the market, it is important to establish a high-efficiency machining method and a nondestructive inspection method to assure reliability.

Kyosuke Ai: He entered Kanagawa Prefectural Industrial Research Institute and has been engaged in research, tests, and guidance involving abrasive grain processing. He is mainly tackling fine ceramics grinding from the aspects of normal grinding, creep feed grinding, and supersonic grinding, thereby accumulating data to enable high efficiency and high quality in grinding operations.

Yasuo Tsujisato: He entered Mitsubishi Metal Corporation in 1966, employed in its carbide tool sector, followed by his current work involving the R&D of diamond-CBN wheels. At present, complex and high-precision configurations have come to be demanded for diamond wheels along with the fact that their diffusion exceeds that of general ones. Due to these circumstances, he is tackling higher precision and improved fabricability of diamond wheels.

Kaneshige Oma: He was loaned to Fujitsu, Ltd., from Fujitsu Automation Co. in 1982, and has constantly been engaged in the R&D of manufacturing technologies, such as NC application, die manufacturing, and ultraprecision processing. In relation to this, he is continuing his consulting activities involving the diffusion of technologies in Korea and Singapore. He is currently a member of the Overseas Enterprise Consulting Corp.

Kango Ohira: He is employed by Makino Milling Machine Co., Ltd. Currently he is tackling basic research involving the application and product technology development of grinding and finishing operations by the machining center. He also almost completed the first stage of test processing and data collection on various ceramics, and is recently going forward with selective R&D involving grinding a ferrous material (hardened steel).

Toshihiro Matsumoto: He was employed by Toyo Soda Manufacturing Co., Ltd. (present Toso Co., Ltd.) in 1970, and has constantly belonged to its R&D sector. He was appointed general manager of its ceramics product development office in June 1986, tackling the commercialization of engineering ceramics, such as zirconia, silicon nitride, and mullite.

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FRP Cutting Technology Reported

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(Article by Noboru Iijima, Mechanical System Engineering Course, Engineering Department, Tokyo University of Agriculture and Technology: "Oscillation Cutting Mechanism- FRP's Problems Involving Its Normal Cutting Properties")

[Text] 1. Introduction

Improvements in terms of materials and processes have permitted FRP to find an increasingly wide range of applications in recent years in various sectors, from aircraft and automobiles to sporting goods, as a material featuring excellent corrosion resistance and high specific strength and specific modulus of elasticity. FRP molded products are generally used as they are, while they often need machining, such as cutting, drilling, milling, and turning, when used for mechanical parts. FRP, consisting of two or more types of materials extremely different from each other in their properties, however, is a material best materializing composite characteristics, so that it is vulnerable to strong directional stability, tool wear, burrs, fluff, and layer flaking, resulting in a deteriorated grade in its machined surface, extremely poor machinability, and short life, thereby posing serious problems for its cutting. In this context, it is deemed that establishing FRP cutting technology will not only improve FRP productivity, but will also contribute to permitting its excellent properties to function well and raising its safety and reliability as a structural material.

In this article the effectiveness of the oscillating cutting method for FRP is described through a comparison of normal cutting and oscillation cutting from the standpoint of cutting properties, such as cutting resistance and finished surface roughness, based on our research applying oscillation cutting to FRP processing.

2. Oscillation Cutting Mechanism

It is well known that the micro-oscillation of cutting tools and workpieces exerts an important influence on chip formation, while in a stable cutting state also, oscillation using extremely small amplitudes is caused in machine tools, workpieces, and tools. When the amplitudes of these

oscillation sources become abnormally great due to resonance, etc., chatter will be caused, degrading the finished surface quality of the workpieces. Oscillating cutting here is not the same as oscillation caused by normal cutting, but a stable cutting method in which the rigidity of machine tools, workpieces, tool materials, and tool configurations is scrutinized and extremely fine amplitudes are given to the cutting edge of a tool, while forcefully retaining its regularity.

Figure 1 presents an outline of the supersonic oscillation cutting method. A mechanical or hydraulic method is used for oscillating tools in oscillation cutting, using low frequency oscillation with frequencies of below 500 Hz and amplitudes of about 0.3 mm. When high frequency oscillation, with high frequencies of above 20,000 Hz of the supersonic area and amplitudes of 10-15 μm is used, oscillation is generated in tools by converting electric energy into mechanical energy using a trembler utilizing electrostriction and magnetostriction phenomenon. In supersonic oscillation cutting, as shown in Figure 1, cutting is generally conducted by fixing oscillation sources to the tool box and amplifying the amplitude with the hone, with a cutting tool attached to its tip.

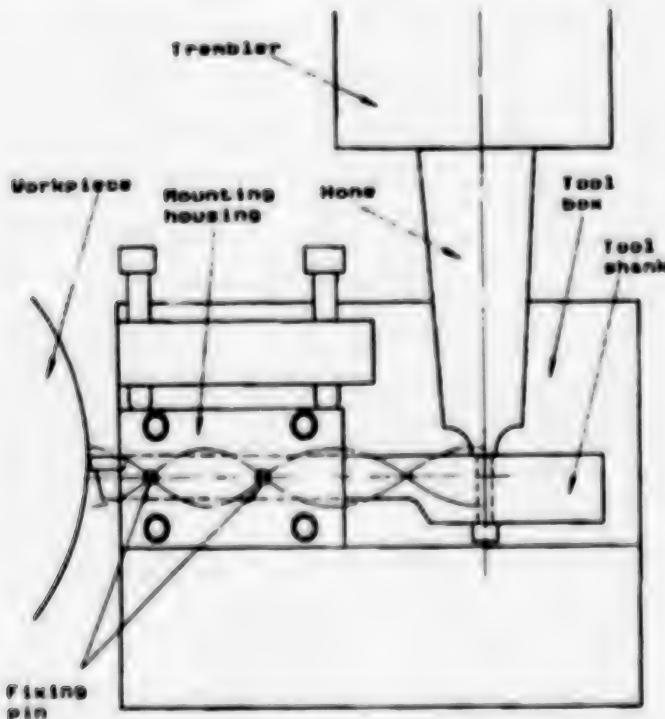


Figure 1. Supersonic Oscillation Cutting Unit

Three tool oscillating directions are considered--those of the main component of force, feed component of force, and back component of force, while it has been confirmed that oscillation cutting can be conducted most effectively when the direction of the main component of force is the same as the cutting direction.

Figure 2 shows a two-dimensional oscillation cutting mechanism. It illustrates cutting at a cutting speed of v while applying sinusoidal forced oscillation to a cutting tool by oscillation drives in the cutting direction with a frequency of f and a one-way amplitude of a . Let us suppose that the tool begins oscillation at the origin o in Figure 2. Then, the pulse-shaped main component of force p_c and back component of force p_t act between A and B to form chips, while the tool and workpiece are separated between points A and C, with no cutting force caused. Between C and D, a pulse-shaped cutting force the same as that between A and B forms chips again. The mechanism is such that periodically repeated contact and release between a tool and a workpiece allow the pulse-shaped cutting force to be generated in succession.

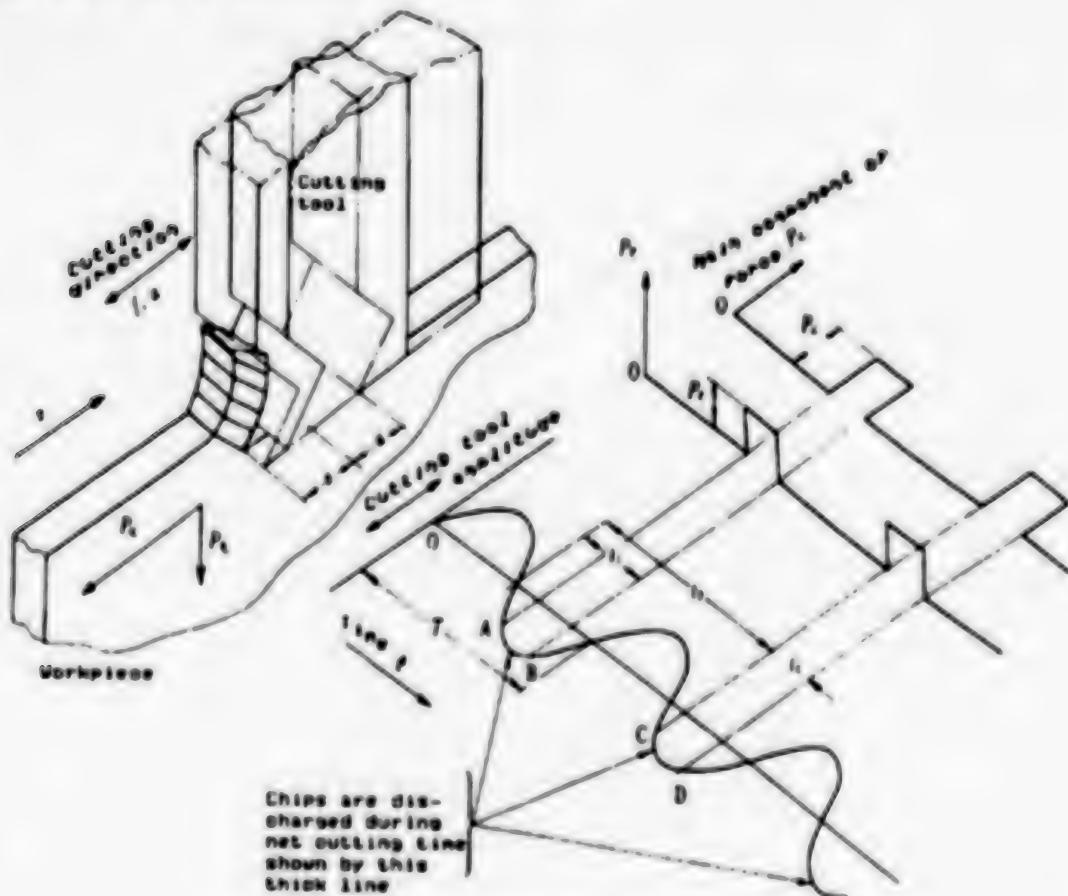


Figure 2. Oscillation Cutting Mechanism

Let the Y-axis be in the tool's oscillation direction and ω be an angular frequency. Then, y , the tool's oscillation displacement in its main kinetic direction, and \dot{y} , oscillation velocity, can be expressed as:

$$y = a \sin \omega t \quad (1)$$

$$\dot{y} = a\omega \cos \omega t \quad (2)$$

In Figure 2, t_1 , representing the time for the tool to begin coming off the chips, is when the tool's oscillation velocity is equal to its cutting speed, shown by points B and D. Then, t_1 can be obtained by the following expression:

$$v = \omega \cos \omega t_1 \quad (3)$$

If $v > \omega$, there is no solution for expression (3), and this will lead to normal cutting when the tool and workpiece remain in contact. Then, v_c , the cutting velocity when the oscillation cutting function is lost, can be expressed as:

$$v_c = \omega = 2\pi af \quad (4)$$

Incidentally, this v_c is referred to as the critical cutting speed, therefore, the condition for effective oscillation cutting can be expressed as:

$$v < v_c = 2\pi af \quad (5)$$

Therefore, when drives providing only low frequencies are used, cutting is conducted at the low cutting speed v , while in order to increase a cutting speed, it is necessary to increase the tool's frequency.

3. Problems in Normal FRP Cutting

As a composite material of a two-phase structure with a relatively soft matrix material mixed with a tough, hard fibrous material, FRP possesses extremely different cutting conditions for its mixed materials, resulting in extremely poor machinability. The problems can be summarized as follows:

(1) The tough, hard fibrous phase is more difficult to cut than the soft matrix phase, with the periphery of fibers vulnerable to elongation and flexing. The cutting of deformed and displaced portions is prone to cause uncut portions or layer flaking, thereby inducing fluff and burrs.

(2) Since its coefficient of thermal conductivity and volume specific heat is low, the cutting of FRP generates higher temperatures than does that of metallic materials at the same cutting speed, and the rate of increase of a cutting temperature to that of cutting speeds is sharp. This often results in deformation due to softening in its processed surface with relatively low heat-resisting strength and poor finished surface roughness, as well as degraded machinability due to the difference in the softening degree between its fibrous and matrix phases.

(3) FRP's hard fibrous phase mixed in its soft matrix phase causes remarkable wear of the cutting edges, which prevents the edge configuration required for cutting it from being retained long.

As countermeasures to the above from the standpoint of tools, it is necessary to develop wear-resistant tool materials, and select and devise a

tool configuration free from layer flaking, fluff, and unfinished cutting. There is, however, a limit to coping with these problems through tool improvements alone, and a drastic solution cannot be obtained for the case of an FRP consisting of materials with extremely different properties.

In this context, we decided to apply oscillation cutting to achieve normal chip formation and improved finished surface grade by simultaneously cutting a soft matrix and a hard fibrous phase with a cutting edge. This is because, as stated in the previous chapter, in oscillation cutting, the top cutting edge is oscillated like a pendulum, so that the tool comes into contact with the workpiece only at the moment chips are formed, which we deemed would result in relatively less tool wear and heat generation, as opposed to normal cutting where the tool and workpiece are constantly sliding. It is also because it was presumed that the pulse-shaped cutting force of the top cutting edge acting in succession in a cutting direction would be effective as an impulse force for the instantaneous cutting of the fibrous phase.

4. FRP's Oscillation Cutting Properties

In order to obtain basic data on the FRP's oscillation cutting properties, the one-way continuous CFRP shown in Figure 3, was manufactured to undergo two-dimensional cutting with the fiber angle θ changed as shown in the figure.

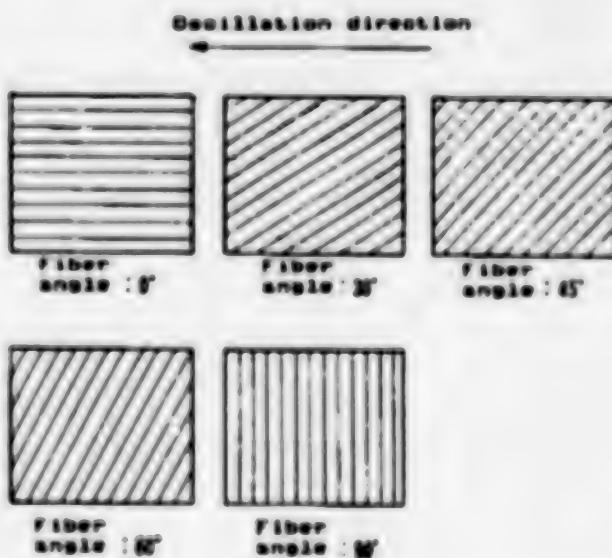


Figure 3. Fiber Angles to Cutting Directions

Figure 4 shows the relationship between cutting resistance (main component of force) and fiber angles with frequencies as parameters. The figure shows that under some oscillation conditions, the cutting resistance rapidly decreases in the whole area of fiber angles, compared with that of normal cutting. In these cases, low-frequency oscillation cutting has been applied at the low cutting speed of 32 mm/min (0.53 mm/s), with expression

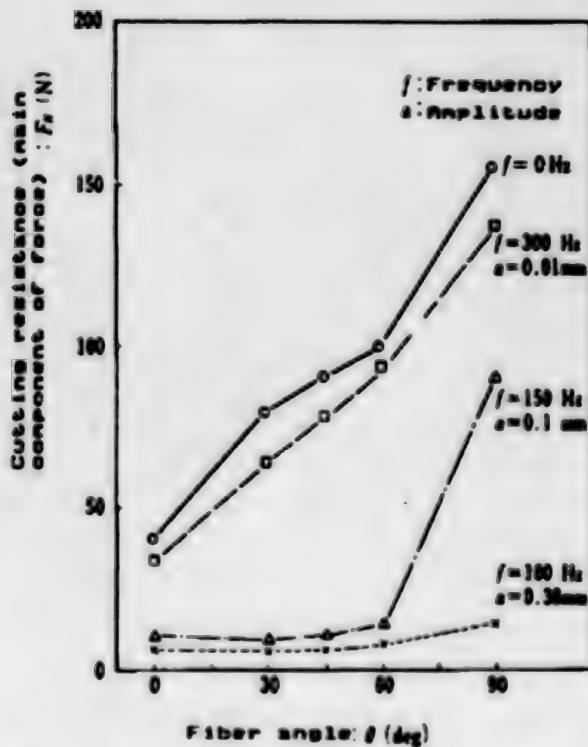


Figure 4. Tool's Oscillation Effect on Cutting Resistance (Main component of force)

(5) satisfied in any oscillation condition with cutting speeds lower than the critical one.

To cite an example of a fiber angle of 90 degrees, use of a 13- μm thick fiber FRP required the extremely short time of about 0.025 seconds to cut a piece of fiber. Since FRP oscillation cutting is conducted as shown in Figure 5, the tool contacts a piece of fiber 2.5 times to cut it when a frequency of 100 Hz is used. With 150 Hz and 300 Hz, the frequency of its impact can be 3.7 times and 7.4 times, respectively.

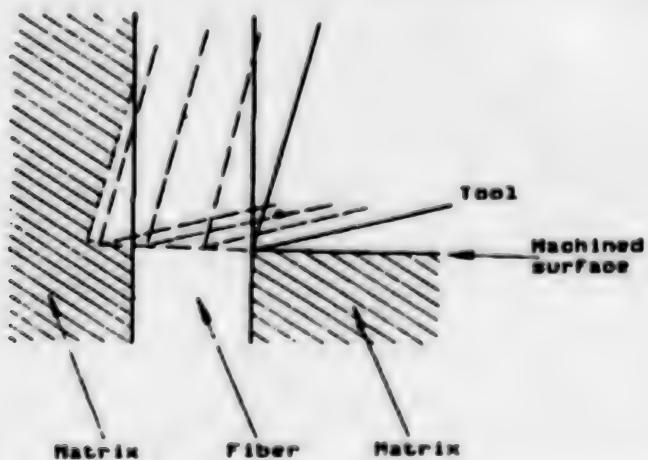


Figure 5. Oscillation Cutting of FRP Fibrous Phase

The frequency of a tool's impact against a piece of fiber increases as the fiber angle becomes smaller, while when the fiber angle becomes 30 degrees, the frequency of impact becomes two times higher than that for the fiber angle of 90 degrees for each oscillation frequency. When the fiber angle is zero, theoretically, the top cutting edge either hits the fibers constantly or does not at all, however, in reality, it is deemed that the probability of the top cutting edge constantly hitting a piece of fiber is low due to the layer flaking of the fiber caused by cutting since the cutting resistance in Figure 4 shows small values. Therefore, apart from the cutting mechanism when the fiber angle is zero, it can be presumed that the reason for the fiber angle decreasing as the cutting resistance decreases, as shown in Figure 4, is, judging from an increase in impact frequency, that the fractionized impact causes fractures and cracks to develop in the fiber.

A comparison of calculated impulse forces under individual oscillation conditions with those for 300 Hz, as a standard, shows that the forces for 150 Hz and 100 Hz increase 2.5 and 4.2 times, respectively, due to their corresponding amplitudes, while the difference in cutting resistance according to oscillation conditions in Figure 4 shows that the cutting resistance decreases according to the magnitude of impulse force. Therefore, it is presumed that a trend similar to normal cutting can be found in oscillation cutting when the impulse force generated in the tool cutting edge is extremely small.

Figure 6 shows the relationship between the depth of cut and cutting resistance (main component of force) in supersonic oscillation cutting and normal cutting. In normal cutting, in which the tool and workpiece are constantly in contact with each other during operation, if the fiber angle is constant, the deformation resistance caused by the operation for a machining surface changes according to the depth of cut, showing that the cutting resistance follows a trend according to that as well.

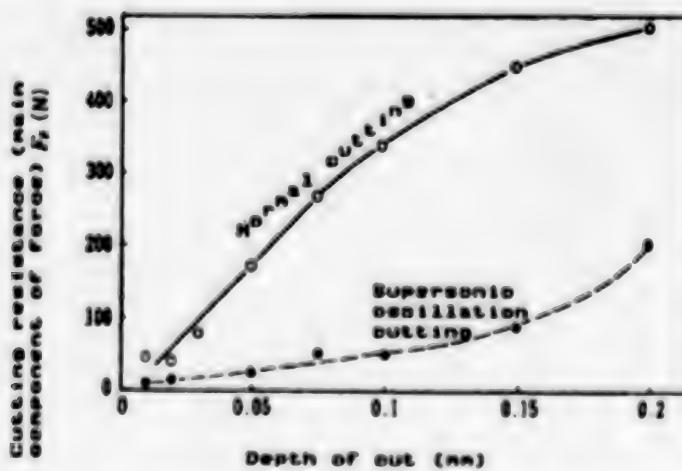


Figure 6. Relative Changes Between Depths of Cut and Cutting Resistance Values

On the other hand, in supersonic oscillation cutting, since the net time of one cycle, as is the case with Figure 6, is as short as one-twenty-thousandth of a second, cutting of its fiber and matrix is conducted instantaneously immediately before a workpiece undergoes elastic, plastic deformation by processing, and the tool almost simultaneously comes off the workpiece, resulting in a low average cutting resistance and significant influence on changes in the depth of cut when compared with those of normal cutting. An increase in the depth of cut, however, results in a relative increase in the quantity of chips to be removed, while oscillation conditions restrict time and amplitudes to remove them to an extremely narrow range, so that an increase in the quantity of chips between the tool and the workpiece prevents the former from coming off the latter completely, thereby making oscillation cutting less effective and rapidly increasing cutting resistance. In Figure 6, it is presumed that the critical depth of cut is 0.15 mm which is found during the transit period when cutting resistance rapidly increases. Therefore, in oscillation cutting it is necessary to select depths of cut adaptable to oscillation conditions, such as frequency and amplitude.

Figure 7 shows the relationship between the fiber angle and finished surface roughness (R_{max}) in low-frequency oscillation cutting. Compared with normal cutting, oscillation cutting provides good finished surface roughness for individual fiber angles, as low as less than one-sixth, depending on the oscillation conditions and fiber angles.

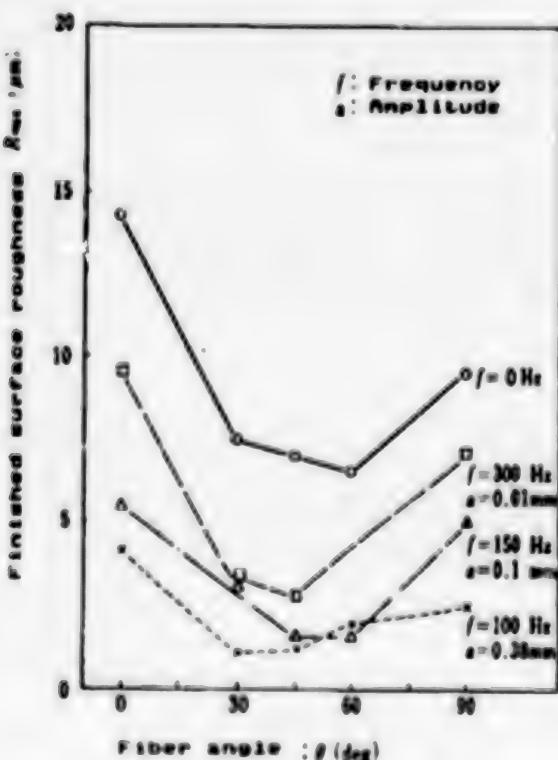


Figure 7. Tool's Oscillation Effect on Finished Surface Roughness

The quality of the FRP cutting surface roughness can be judged by how sharply the fiber is cut on the same plane as the cutting surface, so the influence by the fiber angle cannot be neglected with the FRP's strong directional stability. Photo 1 shows instantaneous photographs of two-dimensional normal cutting of GRFP using a planing tool with a rake angle of 15 degrees.

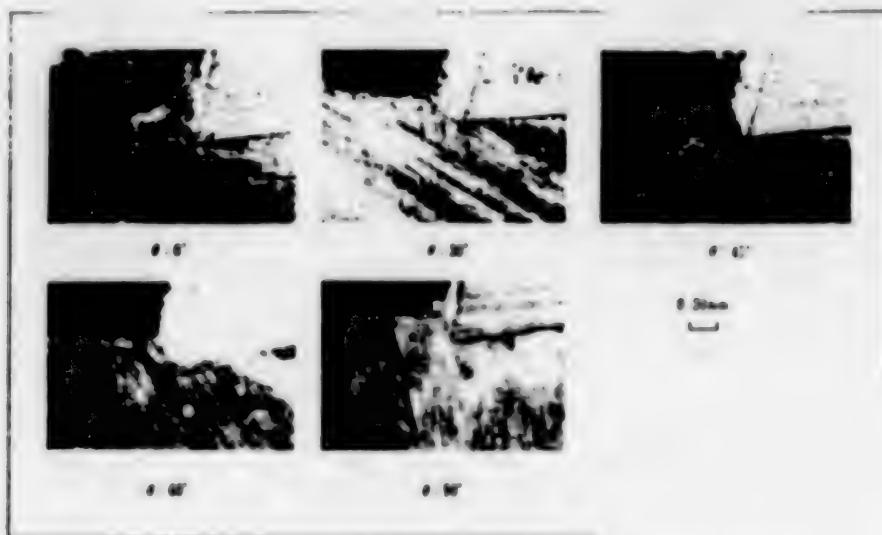


Photo 1. Relationship Between CFRP's Fiber Angles and Chip Formation

When the fiber angle is zero, cracks occur in the fiber direction and induce flaking and falling of the fiber, so that the finished surface roughness obtained by both cutting methods is rough, while that obtained by oscillation cutting in breaking fiber by impulse force is smooth compared to that of normal cutting, since the former method permits fewer cracks in the fiber direction. When the fiber angle is 90 degrees, fiber prevents chips from being shared, allowing discontinuous massive ones to be discharged in remarkable deformation, while oscillation cutting permits less deformation, resulting in relatively good chip formation. When the fiber angle is in the area between the above two, the direction of the shear surface is restricted by the fiber direction in quite a wide area of fiber angles. However, since the chip forming mechanism resembles that of metal cutting, shearing fiber by the tool cutting edge is conducted relatively easily, with normal chips also formed in normal cutting. Therefore, it can be concluded that both cutting methods--normal and oscillation--provide good results in finished surface roughness for fiber angles of 30-60 degrees, resulting in increased roughness for their fiber angles.

Photo 2 [not reproduced] shows cutting finished surfaces for the fiber angle of 90 degrees. In normal cutting, shown in (1), the matrix is very rough on the surface, with large convexes occurring here and there in the peripheries of the fiber's cross sections, and an influence by, in addition to the deformation stated in Photo 1, the difference in the property-related deformability of the fiber and matrix is found on the finished

surface. Meanwhile, in oscillation cutting in (b), the matrix is less rough on the surface and the peripheries of fiber are relatively flat, thereby showing the matrix and fiber being cut instantaneously before they undergo deformation by pulse-shaped cutting force.

As for the grade of the FRP finished surface by cutting, problems are posed by the lack of cutting as well as the finished surface roughness. Some of the uncut portions retain their configurations, but the majority undergo layer flaking of fiber due to stress or dislocation during processing for fluffiness, so that they not only spoil the accuracy and appearance of the product, but also, when used as components, are prone to cause cracks and moisture absorption, thereby often spoiling the reliability.

We then decided to refer to such uncut portions extruding into free space as burr, obtained the burr ratio by the following expression, and experimented to obtain its determination:

$$\text{Burr ratio} = \frac{B - A}{A} \times 100 \text{ (percent)} \quad (6)$$

where A represents the breadth of a machining sample before cutting and B that after cutting.

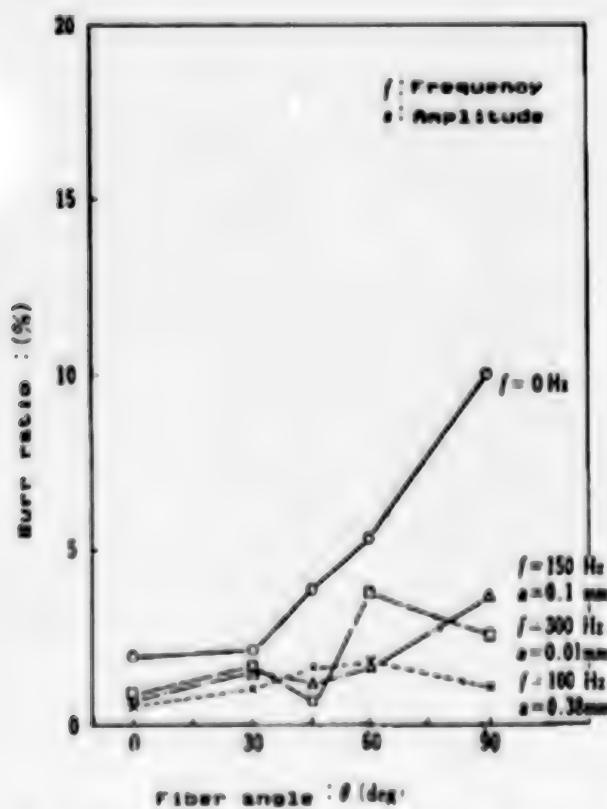


Figure 8. Tool's Oscillation Effect on Burr Ratio

Figure 8 shows the relationship obtained by expression (6) between the fiber angle and burr ratio under each oscillation condition. The figure shows that in normal cutting, the burr ratio tends to increase rapidly as the fiber angle increases, while its oscillation cutting, the burr ratio is low under any oscillation condition compared with normal cutting, with little perceptible influence by the fiber angle, proving that oscillation cutting is effective for burr prevention in FRPs.

Photo 3 [not reproduced] is taken by an optical microscope, showing the GFRP sides after cutting at the fiber angle of 45 degrees. In normal cutting shown in (a), it is distorted as it is pushed toward the cutting direction by the constant contact of the cutting tool, so that lack of cutting occurs in some portions, causing layer flaking and thereby inducing fluff and burrs. In addition, directly below the machined surface discolored portions are found which are processing-affected layers influenced by heat, dislocation, and deformation in cutting. On the other hand, in supersonic oscillation cutting shown in (6), it is cut almost uniformly on the same plane as the machined surface, resulting in a good finished surface, few uncut portions and burrs, and no discolored area directly below the machined surface, thereby proving the result in Figure 8.

5. Conclusion

We experimented with normal and oscillation cutting on fiber angles for which the directions of the fiber, the basic FRP materials, and its cutting were considered, and compared and studied cutting properties obtained by both methods, resulting in the confirmation that oscillation cutting is effective in FRP cutting.

When a wider range of oscillation, conditions and output are conveniently available and equipment, such as compact oscillation drives and associated mechanisms, are improved and developed in the future, it is deemed that oscillation cutting will find a wide range of applications in various cutting operations and undergo systematization as a cutting method for cutting-resistant materials such as FRP, thereby supporting the displaying of the functions of these composite materials.

20117/9365

Hard Material Cutting Technology Described

43064023c Tokyo KIKAI TO KOGU in Japanese Jan 88 pp 32-39

[Article by Takeaki Kitagawa and Katsuhiro Maekawa, Mechanical Engineering Department, Kitami Institute of Technology: "Plasma Hot Machining Unit--Hot Machining of Carbon Steel, High Manganese Steel, Chilled Cast Iron, and Ceramics"]

[Text] 1. Introduction

Theoretically speaking, machining is possible if the relative hardness of a tool to a workpiece is greater; however, it is said that for a tool to function, it needs to have high temperature strength three to five times harder than that of the workpiece. There is a tendency for recent workpieces, referred to as cutting-resistant materials, used in such sectors as the aerospace industry, nuclear power generation, and petrochemical plants, to be harder. They include, for example, high manganese steel, chilled cast iron, titanium alloy, sintered HSS, sintered hard alloy, and ceramics. In machining them, tool materials naturally cannot help but follow the same course as that of sintered hard alloy, cermet, and ceramics.

Paying attention to the difference in relative hardness permits effectiveness to be achieved by methods which introduce measures to decrease work hardness, one of which is hot machining. This method can be used in two ways--heating of an entire workpiece and the partial heating of its machining portions. In this article the latter is described--plasma hot machining involving local softening by plasma heating of a high-hardness material and immediately removing the heated portions. Due to the local heating, it permits the degradation to be controlled to the minimal accuracy in machining dimensions and surface conditions, which has been regarded as a disadvantage of conventional hot machining when heating an entire workpiece.

2. Plasma Hot Machining Unit

Partial heating of workpieces includes resistance welding, arc, and high frequency induction. After taking into consideration high heating speeds and their application to nonmetallic materials, we adopted the plasma arc shown in Figure 1 and surface heating by a plasma jet. Figure 2 shows the

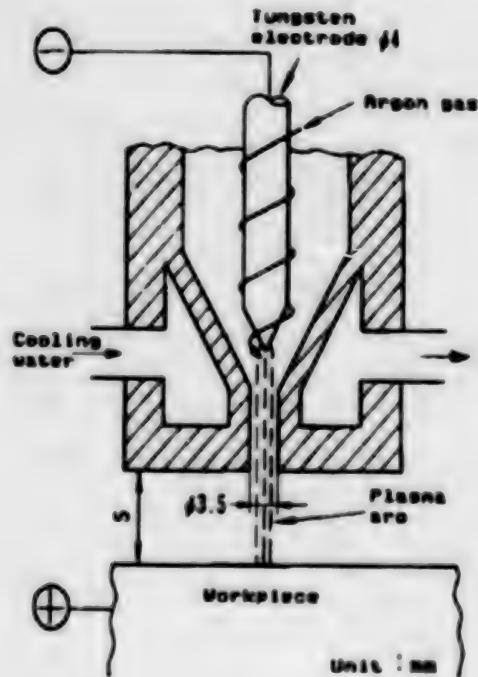


Figure 1. Plasma Heating (By plasma arc)

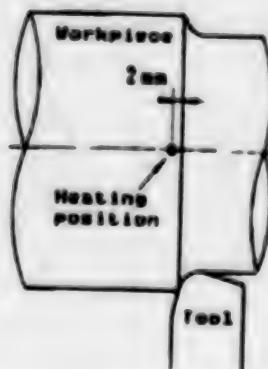


Figure 2. Heating Position

heating position, while Figure 3 shows a schematic drawing of a plasma hot machining unit, which consists of a large high-speed lathe, power source, argon gas arc controller, plasma torch, and cooling water. The unit offers two features--selection is permitted by changing over switch S_2 of either the plasma arc heating between the tungsten electrode and workpiece or the plasma jet heating between the electrode and nozzle, and relatively easy modification of an argon gas arc welding machine into its modified version is possible.

Figure 4 shows an example of a measurement of the unit's heating ability. Heating was conducted by a jet system using a plasma torch with a nozzle aperture of 3.5 mm to examine the influence on the heating temperature of

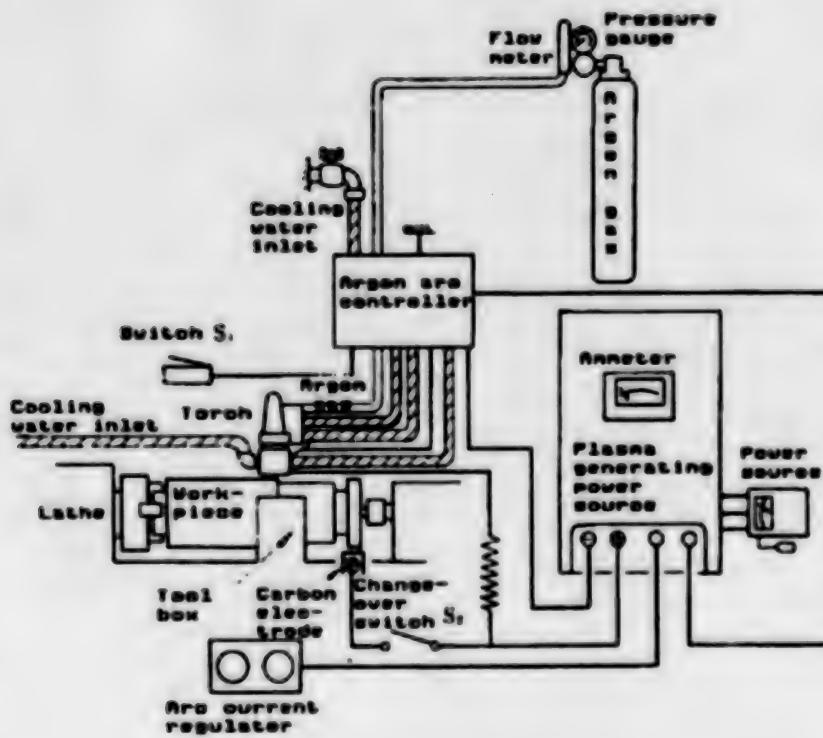


Figure 3. Block Diagram of Plasma Hot Machining Unit

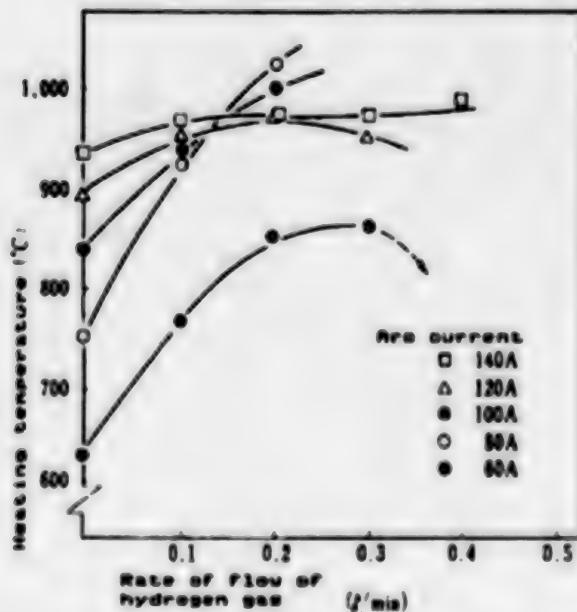


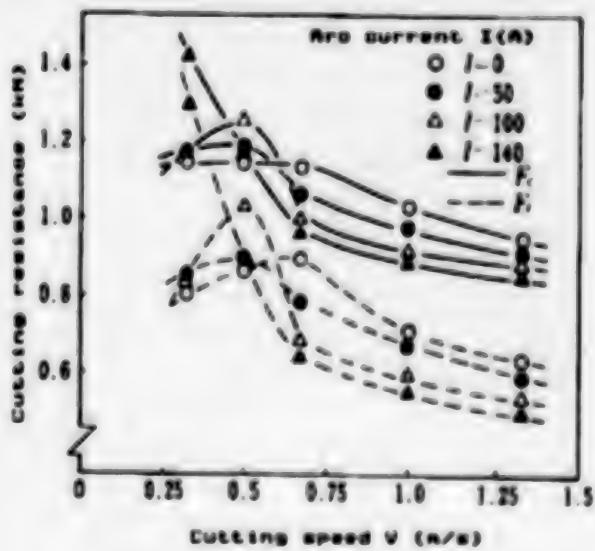
Figure 4. Influence of Hydrogen Gas Addition on Heating Temperature
(When machining is not conducted)

the addition of hydrogen gas to the argon gas (rate of flow, 15 l/min), used as the operating gas, with the distance between the nozzle and the workpiece set at 3 mm. Temperatures during nonmachining periods were measured by an infrared radiation thermometer, set at 270 degrees, behind the heating point. A hollow cylindrical zirconia rod with a diameter of 235 mm was used as a workpiece at a peripheral speed of 10 m/min. Attention must be paid to the fact that the heating temperature depends on such heating and machining conditions as feed, machining speeds, and work materials. With metallic materials with good conductivity, the plasma arc system provides higher heating ability. Photo 1 [not reproduced] shows plasma hot machining of a cylindrical rod in its peripheral longitudinal direction by the same unit.

3. Application Examples

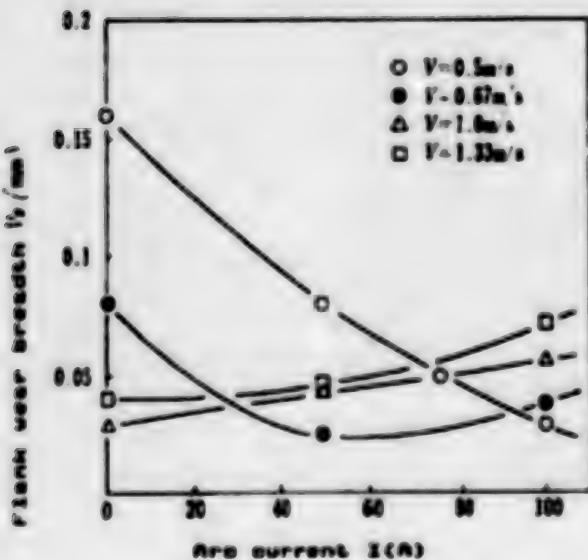
(1) Hot Machining of Carbon Steel

Carbon steel, no longer a cutting-resistant material, presents problems involving increased flank wear and degraded finished surface accuracy under relatively low speed machining conditions, causing a built-up edge. Figure 5 shows the relationship between the cutting resistance and cutting speed in the plasma hot machining of 0.46 percent C carbon steel. To the left of the speed providing the maximum value of cutting resistance, machining is shown which involves a built-up edge, however, plasma hot machining has shifted its speed area further left to the low speed side. Along with this, flank wear decreases, as shown in Figure 6, toward the minimum value, which is due to the plasma heating causing the built-up edge to be smaller or to disappear.



Workpiece: 045C carbon steel
 Tool: Carbide P20 (8, 9, 6, 6, 15, 15, 8)
 Feed: 8.2 mm/rev
 Depth of cut: 2 mm
 Dry machining

Figure 5. Cutting Resistance in Built-up Edge Producing Speed Area



The machining conditions are the same as those for Figure 5.
Machining distance: 500 nm

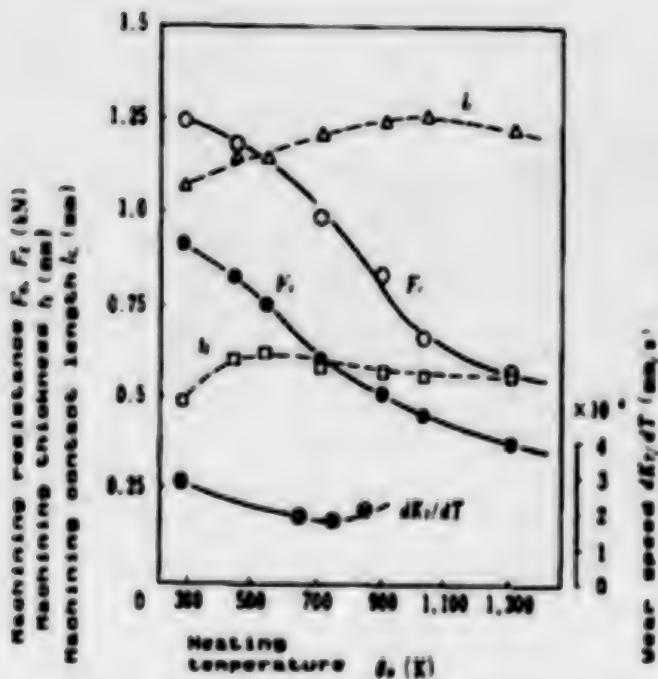
Figure 6. Relationship Between Flank Wear and Arc Current

(2) Hot Machining of High Manganese Steel

High manganese steel has excellent mechanical and physical properties, such as high toughness, wear resistance, and nonmagnetism, as well as a relatively low price, so it finds applications often. However, due to its high hardness, high work hardening property, and low thermal conductivity, it has long been known as a cutting-resistant material.

Photo 2 [not reproduced] shows an example of the finished surface roughness of an 18-percent-Mn austenitic stainless steel improved by plasma hot machining. Chatter caused by normal machining has been successfully removed by shifting to hot machining using a 50-A arc current. Figure 7 shows cutting resistance (main component of force F_c , feed component of force F_t), chip thickness (t_2), chip contact length (l_c), and crater wear speed (dK_r/dT) in plasma hot machining. As the heating temperature increases, the cutting resistance and tool wear decrease while the chip thickness and contact length increase.

We used the numerical simulation method to study why such changes occur in machining conditions in plasma hot machining, with an example of the calculation results shown in Figure 8. Figure 8(a) shows the temperature distribution within a workpiece, including chips, while (b) shows that of flow stress. In both, broken lines indicate normal machining and solid lines show hot machining at a temperature of 500°C. Forced heating causes a sharp temperature gradient on the workpiece surface, which decreases the flow stress. This results in decreased machining resistance, however, the machining thickness, chip contact length, and curl radius, on the contrary,



Workpiece: High manganese steel; Workpiece diameter 130-120 mm; Tools: Cemented carbide P20 (0, 0, 6, 0, 0, 0); Machining speed: 0.5 m/sec; Feed: 0.2 mm/rev; Depth of cut: 2 mm; Dry machining; Nozzle aperture: 3.5 mm; Argon gas flow: 15/l/min. A wear test was conducted with tooth shapes of 0, 0, 6, 6, 16, 16, and 0.5 in three-dimensional machining.

Figure 7. Changes in Chip Formation, Machining Resistance, and Tool Wear in Plasma Hot Machining

increase as the plastic deformation area expands on the workpiece surface. If ideal forced heating as deep as the machining thickness is materialized, the rise in temperature of the rake face and finished surface will be controlled and the reduced flow stress is likely to decrease the tool wear (Figure 7).

3. Hot Machining of Chilled Cast Iron

Work hardness permitting machining by a cemented carbide tool is generally said to be H_b 350. We used 2.25 percent-Cr chilled cast iron for this experiment, which was not homogeneous in its hardness, with a maximum hardness of H_b 371.

Photo 3 [not reproduced] presents optical microscopic photography of rake face wear in 7-min machining. Machining of the material at ordinary temperatures is almost impossible due to the noteworthy tool damage, while it is obvious that in plasma hot machining using an arc current of over 100 A, rake face wear in the corner has been unprecedentedly improved. Figure 9 shows changes in the machining resistance, proving the remarkable reduction in the feed component of force F_r due to the increased heating

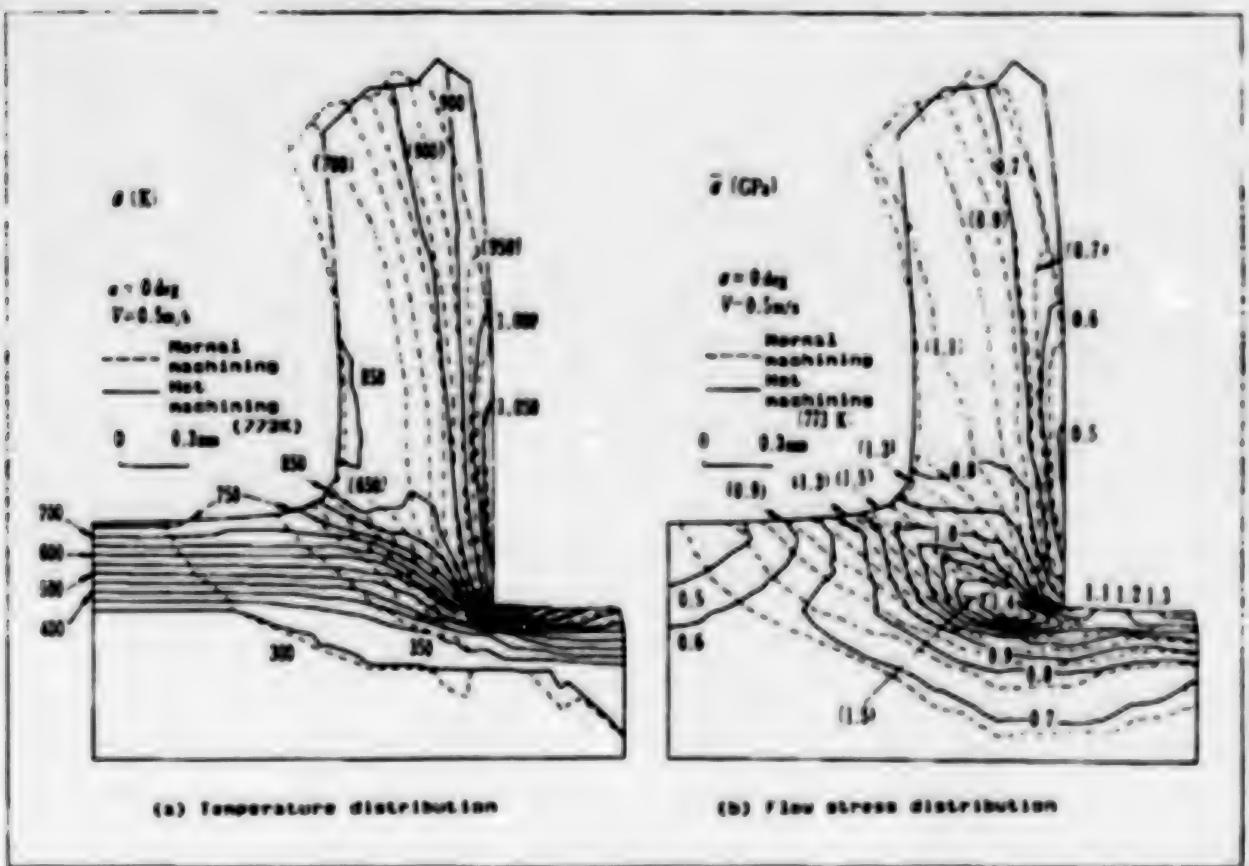


Figure 8. Changes in Temperature and Flow Stress Inside Workpiece in Hot Machining of High Manganese Steel

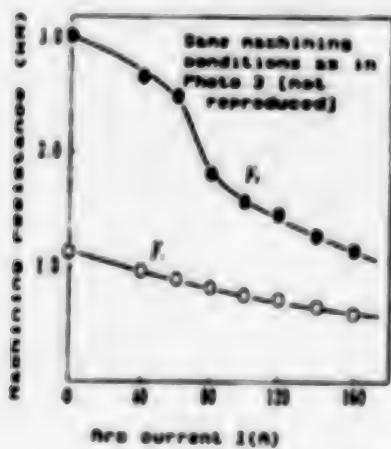


Figure 9. Regulation Between Machining Resistance and Arc Current

temperature. A sharp rise of F_t for an arc current below 60 A is, as is obvious from Photo 3 [not reproduced], due to the development of wear in the tool's corner and rake face. Therefore, it is deemed that it is reduced tool wear rather than the work softening effect by plasma heating

that contributes to the reduced machining resistance with chilled cast iron. Incidentally, 10 types of cemented carbide K with high shock resistance are used for tools with a negative rake angle.

The results above show the effectiveness of the plasma hot machining we developed. Its application, however, should be determined based on the overall outlook after taking into consideration the machining cost.

Figure 10 shows the relationship between the arc current and the total cost required for an hour of machining, including power consumption by the lathe and plasma unit and expenses for chips and argon gas. The figure, although based on a rough calculation, relates that in the plasma hot machining of chilled cast iron, the total cost decreases by a maximum of 50 percent and since arc current exists, the total cost can be held to the minimum.

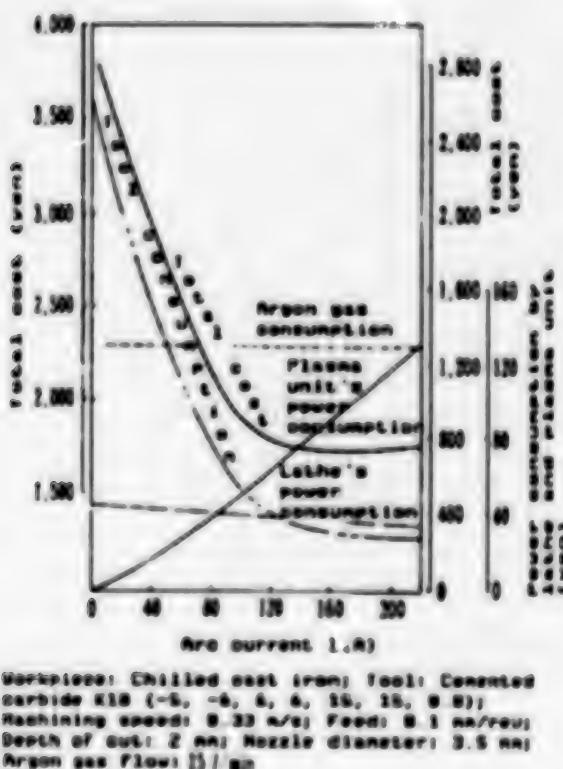


Figure 10. Cost of an Hour of Plasma Hot Machining

4. Hot Machining of Ceramics

Ceramics are made mainly by covalent and ionic bonds in which the bonding between atoms is close, so that chips discharged do not generally form flow shapes based on plastic deformation as do metallic materials, as stated in the previous section. As a result, the finished surface naturally includes typical microcracks and macroscopic defects in discharging brittleness-fracture-type chips. Such a degraded finished surface condition in two-dimensional machining seems to partially hinder ceramic materials from being used as mechanical components. The plasma hot machining of ceramics

not only aims at improving their machinability by providing the relative hardness difference between a workpiece and a tool, as is the case with metallic materials, but also at improving the finished surface conditions by leading the chip forming mechanism from a brittleness fracture type to a plastic deformation flow type.

Plasma hot machining was conducted on five types of ceramics--pyrex, mullite, alumina, zirconia, and silicon nitride. Table 1 shows their principal components and physical properties based on their manufacturers' data, indicating that they all have high hardness and low thermal conductivity not found in metallic materials.

Table 1. Principal Ceramics Components and Physical Properties
(Source by S Co.)

	Pyrex	Mullite	Alumina	Zirconia	Silicon nitride
Principal component	SiO ₂ 80.9%, Al ₂ O ₃ 2.3%	SiO ₂ 49%, Al ₂ O ₃ 47%	Al ₂ O ₃	ZrO ₂	Si ₃ N ₄
Thermal conductivity (cal/cm·sec·°C)	0.003 (100°C)	0.0063 (400°C)	0.035 (400°C)	0.009 (400°C)	0.04 (400°C)
Coefficient of linear expansion (1/C)	3.3×10 ⁻⁶ (0~300°C)	4.5×10 ⁻⁶ (20~1,000°C)	6.9×10 ⁻⁶ (0~400°C)	10.4×10 ⁻⁶ (0~400°C)	3.2×10 ⁻⁶ (40~800°C)
Bending strength (kg/cm ²)	400~700	1,500	8,000	13,000	11,000
Vickers hardness (kg/mm ²)	—	—	~2,200 (1,188)	~1,500 (1,433)	~1,800 (1,766)
Load	500g	(651)	(716)		

Figures in () are actual values

Figure 11 shows changes in the machining resistance, qualitative finished surface roughness, and chip configurations of ceramics other than silicon nitride in plasma hot machining. Pyrex and mullite exhibit an almost similar tendency for their maximum value of machining resistance to appear when the chips shift from the brittleness fracture type to plastic deformation flow type. In addition, P₃/P₁, a back component of force-to-main component of force ratio, becomes smaller than 1 at heating temperatures that permit the minimum finished surface roughness. The same occurs in the plasma hot machining of silicon nitride, to be mentioned later (Figure 13). Except for the fact that a maximum value of machining resistance does not appear, the same results occur with zirconia in that the finished surface roughness is improved by forming complete flow-type chips and that an inverted phenomenon between the back component of force and main component of force occurs at heating temperatures that permit the minimum finished surface roughness. On the other hand, such effectiveness fails to be found in plasma hot machining of alumina. Workpieces were

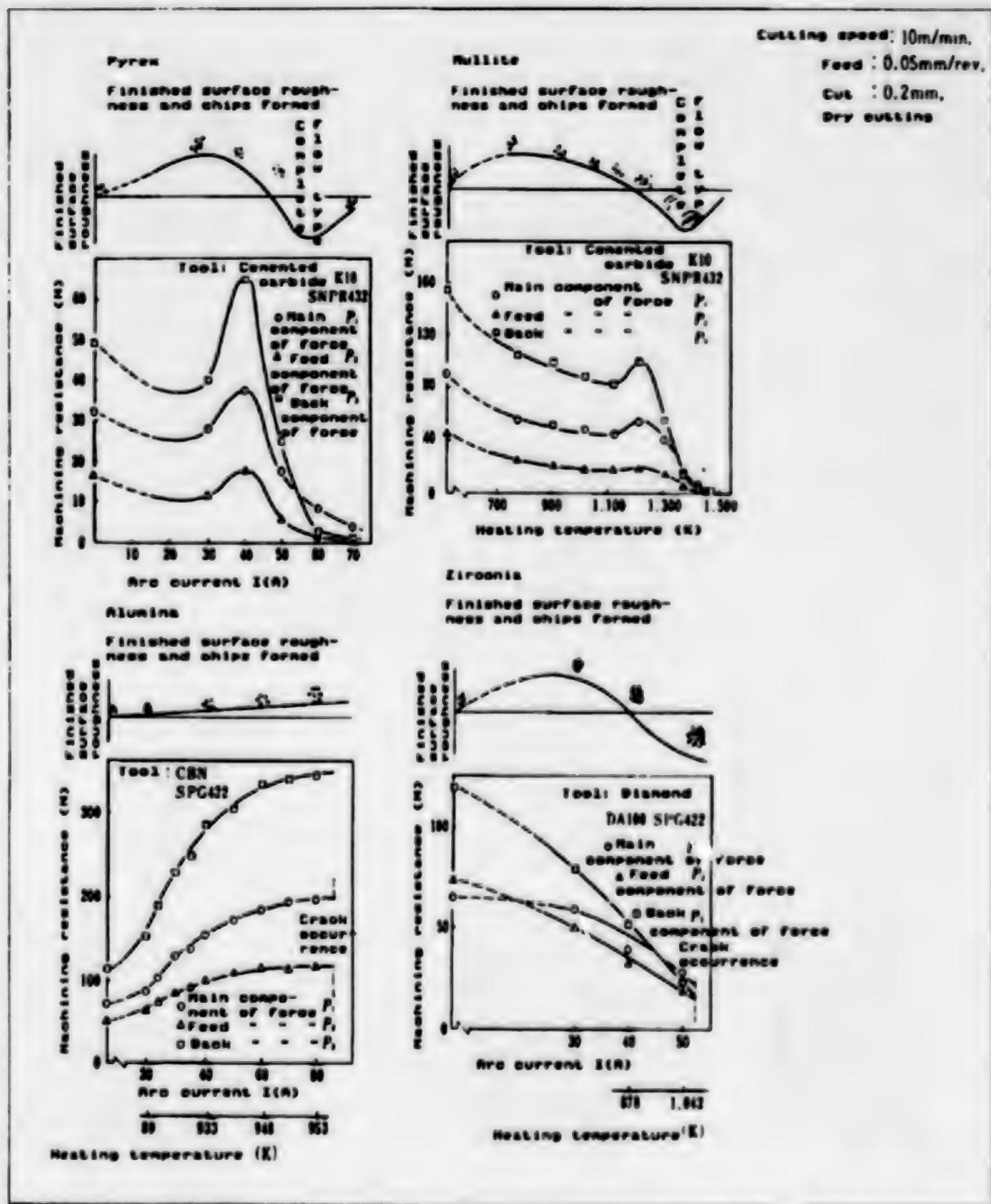


Figure 11. Changes in Machining Resistance, Finished Surface Roughness, and Chip Formation in Plasma Hot Machining

macroscopically fractured at heating temperatures of about 700°C for alumina and 800°C for zirconia, respectively.

Figure 12 shows an example of the measurement of mullite machining resistance and SEM photographs of chips formed and finished surfaces. From these photos, it is obvious that, although the machining resistance shows great fluctuation and the finished surface roughness degrades during the transition of the chip form from a brittleness fracture type to a plastic deformation flow type, the finished surface roughness improves as complete flow-type chips are discharged. Incidentally, along with this transition in the chip form, rake face wear decreased to one-third that in normal machining.

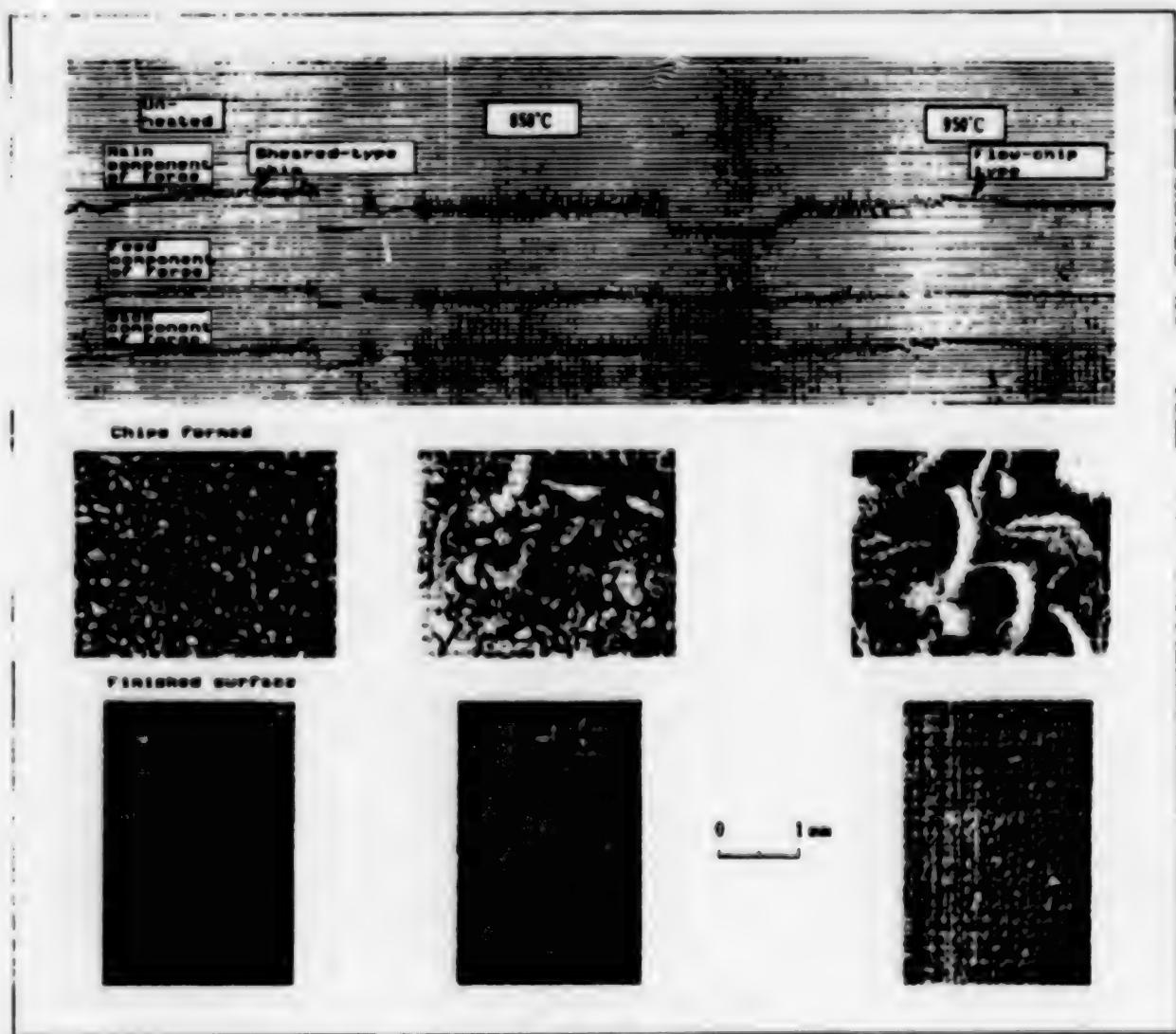


Figure 12. Example of Machining Resistance Measurement and SEM Photographs of Chips Formed and Finished Surfaces
(Same machining conditions as in Figure 11; workpiece: mullite)

Figure 13 shows experimental results of silicon nitride that draw attention to it as a material for tools and mechanical components due to its high strength, toughness, and relatively good thermal shock resistance. It indicates that macroscopic cracks are not caused by plasma heating up to 1,200°C and that changes similar to those in pyrex and mullite occur in chip formation, finished surface roughness and machining resistance.

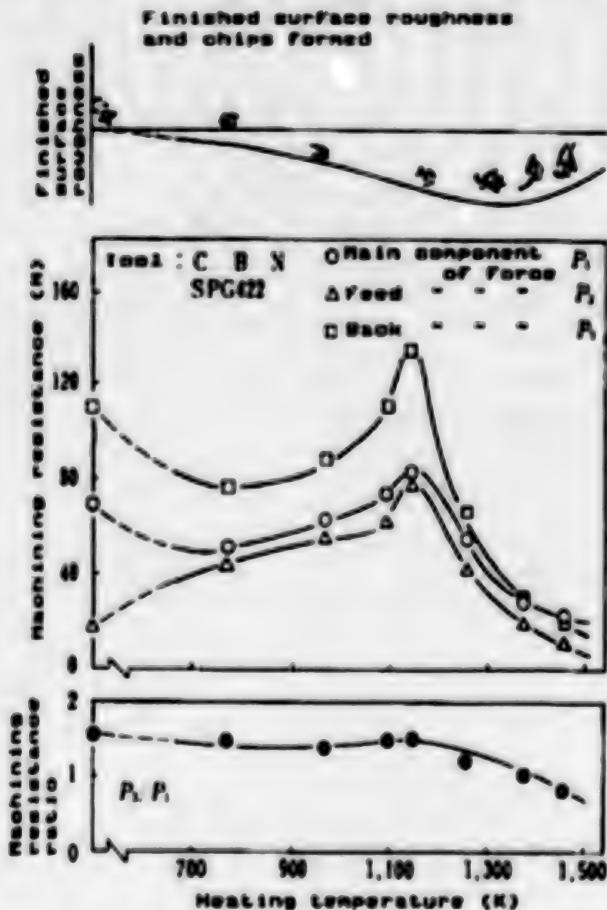


Figure 13. Relationship Between Heating Temperature and Machining Resistance, Finished Surface Roughness, and Chips Formed

Photos 4 and 5 [not reproduced] show SEM photographs of chips formed and finished surfaces, respectively, of silicon nitride, in which chip transition and improved finished surface roughness are found. Finished surfaces (maximum roughness of 8 μm) are shown for purposes of comparison in Photo 5 [not reproduced].

Finally, in Figure 14, the relationship between rake face wear in the corner of a sintered diamond tool and heating temperatures during the plasma hot machining of silicon nitride is shown. It indicates that, at any machining speed during 1-min machining, tool wear decreases substantially as the heating temperature increases. It is believed that this is due to the chemical stability of diamond tools at high temperatures, the decreased working stress on the tool surface due to the

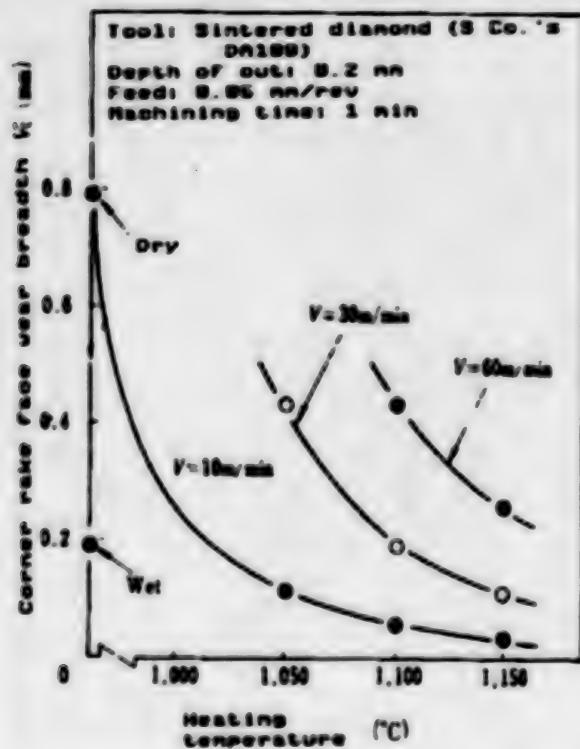


Figure 14. Influence of Heating Temperature on Tool Wear

softened work, and the reduced contribution of abrasive wear. In the machining of silicon nitride, tool costs amount to about 95 percent of the total machining cost, so the application of plasma hot machining to this can be termed promising from the profitability standpoint as well.

4. Conclusion

In this article, a description was given for modifying an argon gas arc welding machine into a plasma hot machining unit with relative ease. As application examples of this method, ultrahard cutting-resistant materials, such as high manganese steel and chilled cast iron and ceramics, and highly brittle cutting-resistant materials, especially silicon nitride, were electively taken up to study changes in their machining resistance, tool wear, chip configuration, and finished surface roughness in plasma hot machining. It was also shown that, in the machining of carbon steel, application under such machining conditions as those that produce a built-up edge is effective in improving tool wear.

Problems, however, do exist. First, the oxidation of finished surfaces during high temperature heating with metallic materials and macroscopic cracks due to thermal stress and shock with ceramics materials do occur. To cope with the former, the heating temperature must be lowered to such an extent as to not cause oxidation in the finished machining. For example, optimum heating temperatures for sintered HSS are about 600°C. For the latter, measures should be taken to study a workpiece supporting method, etc. The selection of optimum heating temperatures currently involves repeated trial-and-error.

Second, an evaluation of the condition of finished surfaces by plasma hot machining is also important. This is because, as is well known with ceramics, microscopic defects or changes in the organization on the surfaces of mechanical components made of them often lead to fatal factors involving their fracture.

20117/9365

Electric Discharge Method for Ceramics Reported

43064023d Tokyo KIKAI TO KOGU in Japanese Jan 88 pp 40-47

[Article by Masanori Yoshikawa, Faculty of Engineering, Tokyo Institute of Technology]

[Text] 1. Introduction

Reports have been made that electric discharge grinding composite processing is effective not only for metallic materials but also for ceramics, which are bad conductors, but they tend to lack persuasive power because the mechanism is not clear. In studying the mechanism of this processing method, it is necessary to consider everything from the fact that the method uses an electrolytic solution as a processing fluid to the effects of the electric discharge processing phenomenon on ceramics in the electrolytic solution.

In order to explain the mechanism of electric discharge grinding composite processing of fine ceramics, the author has been studying the electric discharge processing phenomenon on alumina, silicon nitride, and zirconia in an electrolytic solution employing a whisker tool, a similar phenomenon using an acrylic resin rotational tool containing no abrasive and one using a nonconducting vitrified diamond grinder equipped with a discharge electrode. Based on these studies involving the mechanism of ceramics removal with electric discharge, I will discuss the electric discharge grinding composite processing of ceramics.

2. Discharge Processing Using Whisker Tool

Figure 1 shows equipment that produces an electric discharge with a whisker tool. A nickel whisker tool with a diameter of 0.5 mm and a flat tip serves as an electrode, with a graphite tank with an inner diameter of 60 mm, filled with an electrolytic fluid, serves as the other electrode. A ceramic specimen measuring 5 x 5 x 3 mm is fixed in the center of the container. They are placed on a plate of a balance, and a predetermined pressing force is applied to the whisker tool when the weights on the other plate are adjusted. Single-phase full-wave rectified direct current is used as the power source and an NaOH solution, 2 mm deep, is used as the processing fluid.

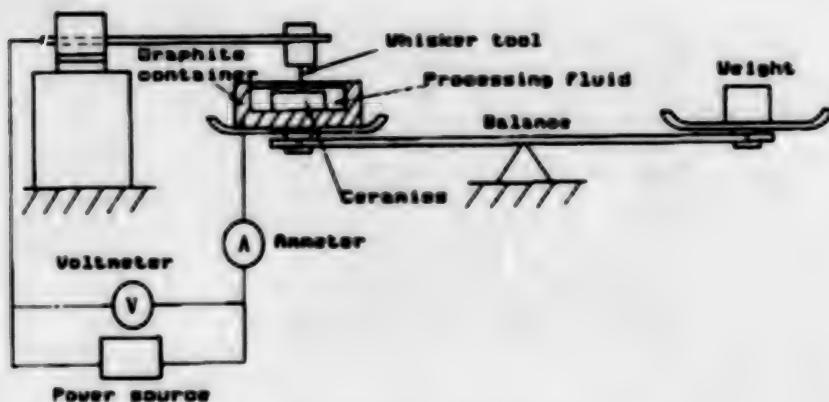


Figure 1. Equipment Producing Discharge

2.1 Discharge Between Whisker Tool and Ceramics

Light is generated between the whisker and alumina. Its spectrum shows that the light is a bright line peculiar to sodium, as shown on Figure 2, attesting to the fact that the light is generated by the sodium contained in the electrolytic solution. From the voltage, it is obvious that the discharge is an arc discharge.

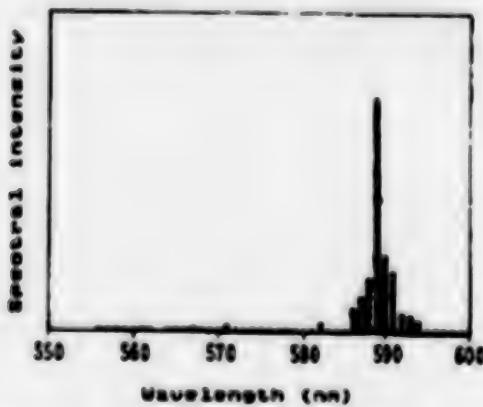


Figure 2. NaOH Solution Spectrum

The voltage-current waveform during the application of a 50-Hz full-wave rectified voltage between the electrodes is shown in Photo 1. When the voltage is low, the waveform indicates an electrolytic condition, as shown by A and C in the photo. This electrolytic current increases in accordance with an increase in the voltage between the electrodes. The ceramic surface does not change in this electrolytic current range.

When the voltage between the electrodes rises, the current between the electrodes rapidly decreases, as shown by B in the photo. Photo 2 is the Lissajous figure representing the relationship between the interelectrode voltage and current, obtained to observe the details involved in this phenomenon. Even within the current declining range, different moves are

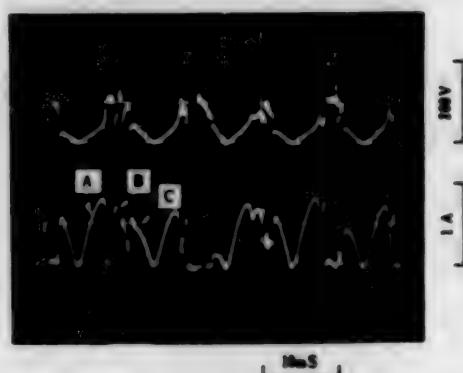


Photo 1. Voltage/Current Patterns



Photo 2. Voltage/Current Lissajous Pattern

seen at B_1 and B_2 . At B_1 , the current between the electrodes falls, but the voltage keeps on rising. This is due to the generation of bubbles. At B_2 , the voltage also decreases. This is because bubbles, which have become insulating film, break, generating an arc discharge. When the discharge brings down the voltage, the condition between the electrodes returns to the original state C.

2.2 Ceramic Materials and Material Removal

Photos 3 and SEM photos showing processing marks left on the ceramics when an electric discharge is conducted for 3 minutes at 50 V, with a whisker serving as the negative electrode and pressing power set at 0.3 N, using a 20 percent NaOH solution as the processing fluid. Figure 3 shows sections of these marks. On alumina and alumina silicon nitride (ASN), processing marks 85 μm and 230 μm deep, respectively, are observed. Marks about 0.25 μm deep are observed on yttria alumina silicon nitride (YASN), while those on magnesia silicon nitride (MSN) can be seen through SEM observation, but cannot be recognized through shape measurement.

Observation of the removal process on ASN with the passage of processing time proves that the removal starts from a point close to the whisker's

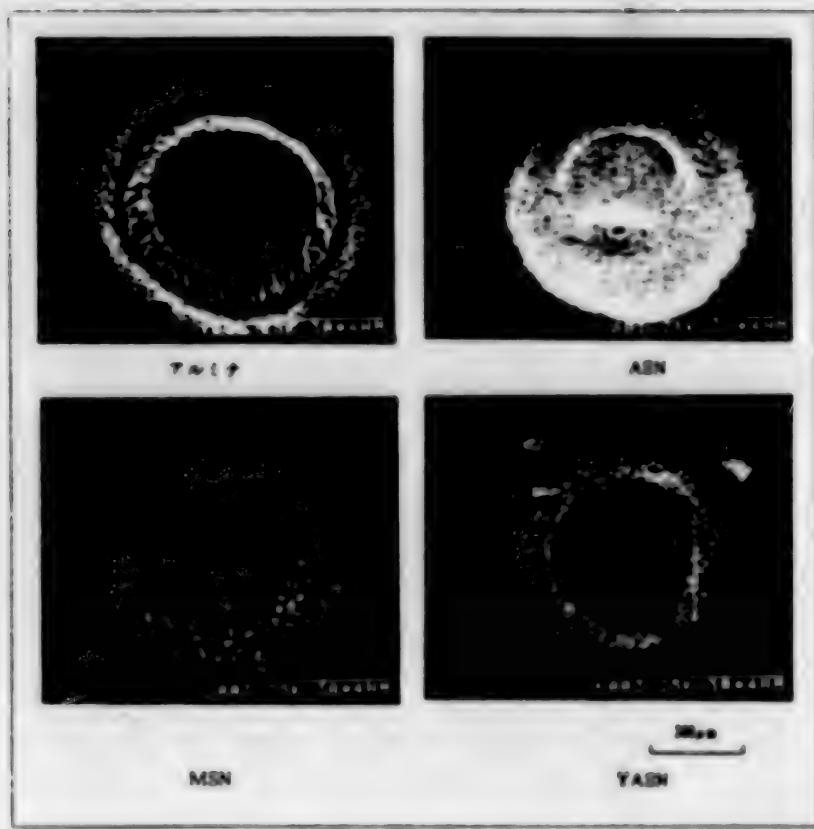


Photo 3. Process Traces Produced on Ceramics Workpieces

external edge and progresses in the direction of depth, then expands to a point directly below the whisker.

The sintering of silicon nitride, reacting with the oxide layer of the particle surface and the sintering assisting agent, produces a liquid phase. Densifying is said to progress via this liquid phase, with the wider the liquid phase around the particle, the higher the density. The liquid phase remains in the grain boundary as a glass phase after cooling, greatly affecting the high-temperature strength of the formed body. An observation revealed that the material removal started from the grain boundary. This means that the grain boundary can be removed easier than silicon nitride particles. As for ASN, the larger alumina content results in greater removal by the whisker. This is due to a larger glass phase.

2.3 Electrical Conditions and Material Removal

To determine the path of an electric current during processing, 3-mm thick ASN with a lead wire was embedded in polyester resin so that the current would not flow through the processing fluid, and a voltage of 50 V was applied in a 20 percent NaOH solution. But the current did not flow and no processing marks were observed. This means that an electric current runs through the processing fluid, not the ceramics.

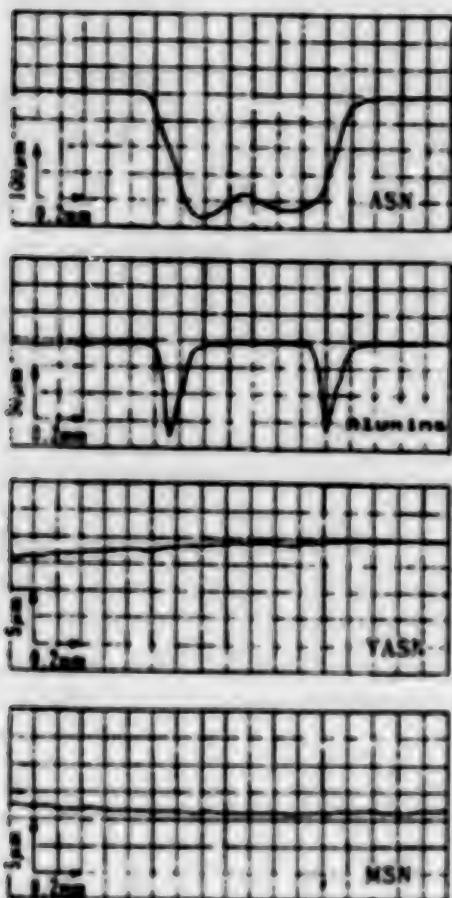
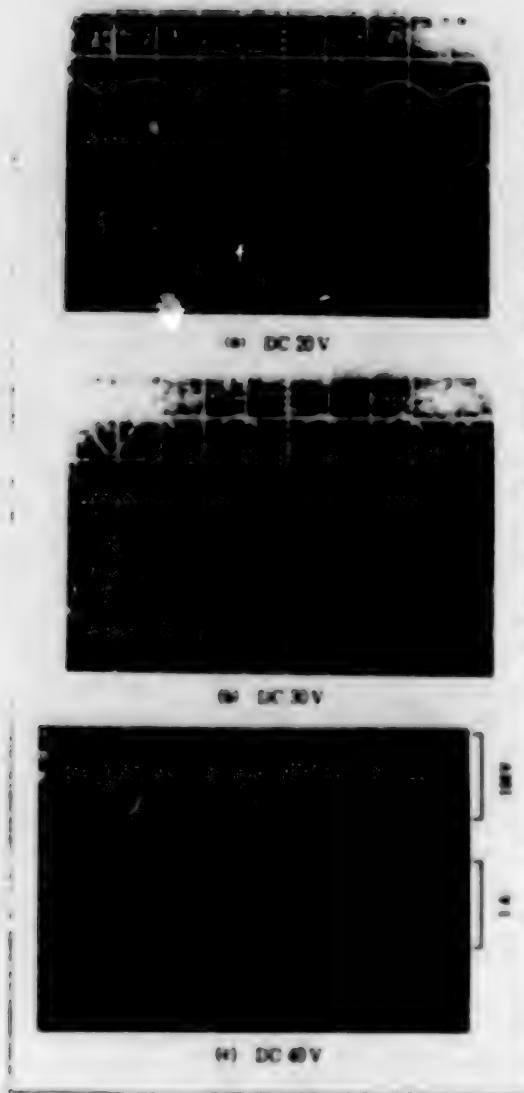


Figure 3. Sections of Processing Marks

Photo 4 illustrates current-voltage waveforms when processing marks appear on alumina and when they do not appear, depending on the voltage. In (a), where the voltage is 20 V and no processing marks were left, the voltage and current go up and down proportionally, whereas in the cases of 30 V, (b), and 40 V, (c), the voltage and current rise proportionally to around 50 V and then the current falls sharply and the voltage and current fluctuate wildly. At that time, the fluid surface near the whisker rises due to the bubbles generated below, and the whisker is enveloped in orange flames. This results from an insulating layer being formed by hydrogen gas generated from the surface of the whisker, the negative electrode, and a discharge occurring between the whisker and the electrolytic fluid via that layer.

Such a discharge phenomenon occurs only when the current-voltage waveform is like those shown in (b) and (c). Similar waveforms are observed when other ceramics are used, but the threshold current for discharge is larger at the low processing fluid density of 5 percent. This is due to the conductivity becoming lower as the density gets lower, requiring a larger current to generate the gas forming the insulating layer.



**Photo 4. Voltage/Current Patterns
(Above: Voltage; Below: Current)**

2.4 Removal Mechanism

SEM observation of the processing marks, shown in Photo 5, proves that particle sizes of the marks on alumina and ASN are almost equal to ceramic grain sizes. This indicates that the grains separate from the grain boundary, then get processed. On YASN and MSN with small processing marks, corrosion of the grain boundary is observed.

Since the processing marks are of a corroded structure, the elution amount of ceramics in the 20 percent NaOH solution was calculated. At a solution temperature of 30°C no elution was observed, even after 30 hours of immersion. After 30-minute immersion at a temperature of 120°C, elutions of 35×10^{-3} mg/mm² and 5.16×10^{-3} mg/mm² were observed for ASN and alumina, respectively. Slight elutions of 5.1×10^{-4} mg/mm² and 2.4×10^{-4} mg/mm² were observed for YASN and MSN, respectively. The order of the

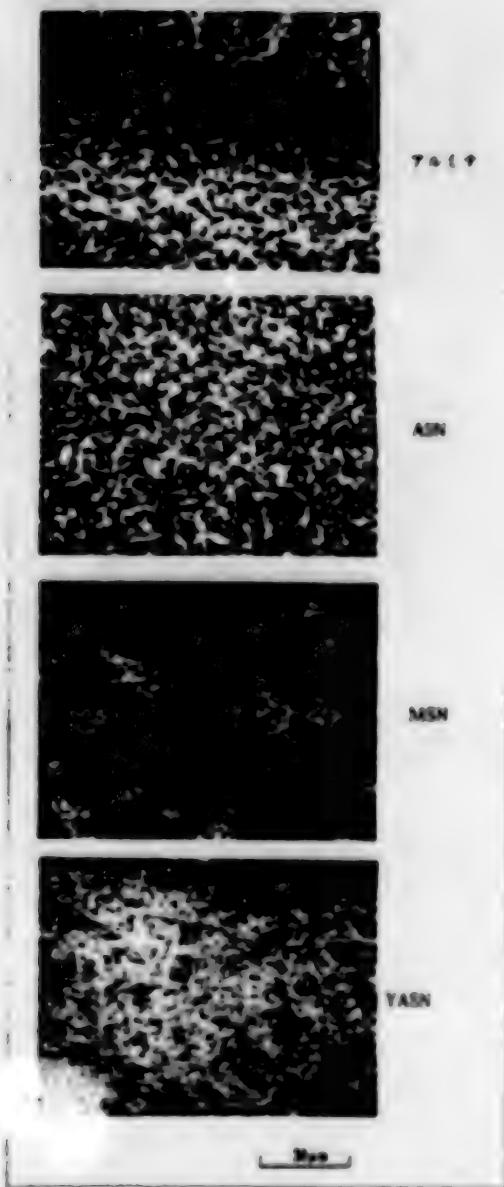


Photo 5. SEM Observed in Process Trace Marks

elution amounts was the same as the order of the amounts removed by discharge, attesting to the fact that removal by discharge is chiefly attributable to corrosion.

Since removal is thought to occur through corrosion when the processing fluid is heated to a high temperature by discharge, I studied removal amounts on ASN using different processing fluids. NaF, NaNO₃, and NaOH fluids were employed as the processing fluids and experiments were conducted as follows to ensure the same electric discharge conditions. The generation of discharge requires the whisker tool to be enveloped by gas generated by electrolysis. The amount of gas generated depends on the electrolytic current and, therefore, similar discharging conditions will be

obtained if the conduction of the processing fluids is the same. Based on this idea, the conduction of each processing fluid was set to that of an NaF saturated solution, 6×10 S/cm. Density was 4.0 percent, 6.2 percent, and 1.2 percent, respectively. When 70 V of electricity was applied for 5 minutes, discharge started at around 64 V in each fluid. It was confirmed by voltage and current waveforms that the condition continued for 5 minutes. Processing marks obtained are as shown in Photo 6. Although discharge conditions were almost the same, the amount removed was the largest when NaF is used, followed by NaNO₃, and NaOH. This means that material removal occurs not through discharge, but by dissolution through the processing fluid heated by the discharge.



Photo 6. Process Trace Marks When Process Liquid Is Added

Based on the study results, a model has been constructed to represent the mechanism of ceramics removal in a processing fluid with a whisker tool serving as the negative electrode, as shown in Figure 4. As in (1), an insulating layer is formed around the whisker by gas generated through electrolysis of the electrolytic solution. Then, discharge is made via the layer, as shown in (2). At this time, the processing fluid around the whisker is heated, and the heated fluid corrodes and removes ceramics. The removal process is shown in (3). As in (4), the processing fluid enters

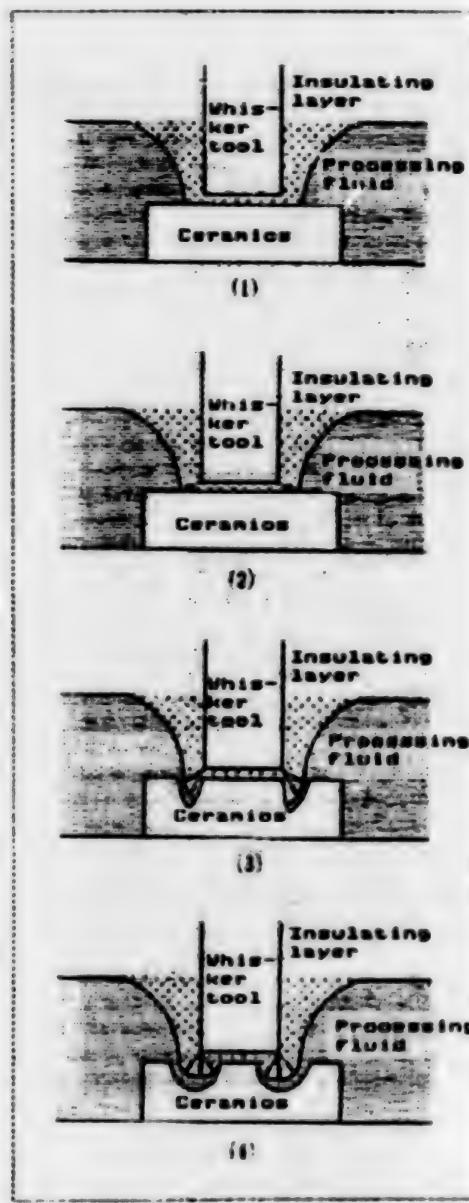


Figure 4. Model of Ceramic Removal Mechanism

the removed area, spreading the removal from the circumference to the area directly below the whisker.

3. Discharge Processing by Rotating Tool

In studying material removal by discharge, a rotating tool made of an acrylic disk measuring 80 mm in diameter and 10 mm in thickness, that did not cause mechanical removal and had an embedded electrode, was attached to the main axis of a grinder to simulate a whetstone, and a voltage of 50 V was applied by utilizing the equipment shown in Figure 5. Any discharge occurring was observed visually.

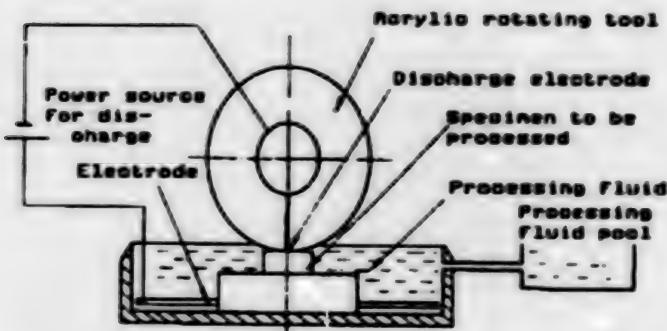


Figure 5. Equipment for Experiments Involving Discharge Removal of Materials Using Rotating Tool

Table 1. Discharge Generation

NaOH density (percent)	Electrode thickness t (mm)				
	0.1	0.3	0.5	1.0	3.0
1.0	x	x	x	x	x
3.0	o	o	x	x	x
5.0	o	o	x	x	x
10.0	o	o	o	o	o

The discharge occurrence depending on the electrode thickness and processing fluid density is shown in Table 1. In that table, o refers to discharge in a stationary state, e refers to discharge in both a stationary state and when the disk was rotated at a speed of 20 revolutions per minute (rpm), and x indicates that no discharge was observed at all, either in a stationary state or when the disk was rotated at speeds of 200 rpm and 2,000 rpm. The experiments prove that the tool rotation narrows conditions for discharge generation when compared with those during a stationary state. At 2,000 rpm, no discharge was observed in this voltage range. But discharge was observed when the electrode was 0.1 mm thick and the voltage was 80 V. Since the occurrence of discharge requires the envelopment of the electrode with the gas generated, higher rotating speeds narrow the range of discharge generation.

The processing of ceramics was attempted using a rotating tool with an 0.1-mm thick electrode. Materials used were ASN and alumina, the top two materials for large removal amounts in experiments using a whisker electrode. A voltage of 80 V was applied for 10 minutes, with the tool rotating at 2,000 rpm. When the tool rotated by contacting the material, processing marks shaped like a boat bottom, about 10 μm deep, 2 mm long, and 0.2 mm wide, were observed (Photo 7). However, no marks were made when the tool rotated 0.3 mm from the material. The marks cannot have been the result of mechanical removal because a considerable gap in hardness exists between the electrode and ceramics. No marks were observed on alumina in either case.



Photo 7. Vessel-Bottom Shape Process Trace Mark

4. Discharge Processing by Vitrified Diamond Whetstone

The whetstone used was a vitrified diamond whetstone, 100 mm in outer diameter and 6 mm in width, with borosilicate glass used as a bonding agent. Abrasives were irregular-shaped diamond with particle sizes of 140/170 and concentration of 100. Twelve electrodes, a silver plate 1 mm thick each, were placed radially. Table 2 shows the grinding conditions. As shown by Figure 6, half of the whetstone width of 6 mm was in contact with the material to be processed so that the amount of whetstone wear could be obtained. Photo 8 shows the alumina after grinding.

Table 2. Grinding Conditions

Processing fluid	5 percent NaOH solution
Processing fluid conductivity	0.2 S/cm
Fluid flow amount	1 l/min
Whetstone rotations	2,200 rpm
Whetstone circumference speed	700 m/min
Applied voltage	0, 120 V

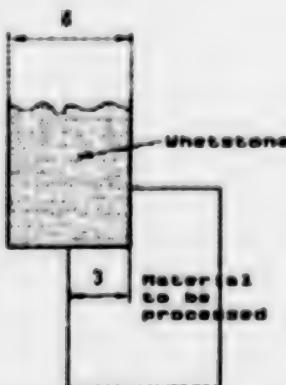


Figure 6. Method for Grinding Experiments

Figure 7 shows the grinding power when the grinding of ASN was conducted with entering of 0.20 mm and table speed of 60 mm/minute. When grinding is done while applying 120 V, the rise in grinding power in proportion to the

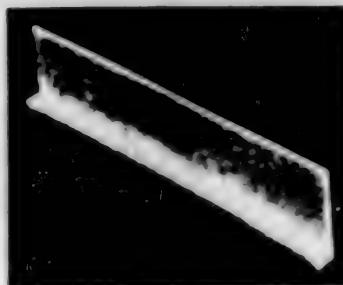


Photo 8. Alumina After Cutting Process Is Done

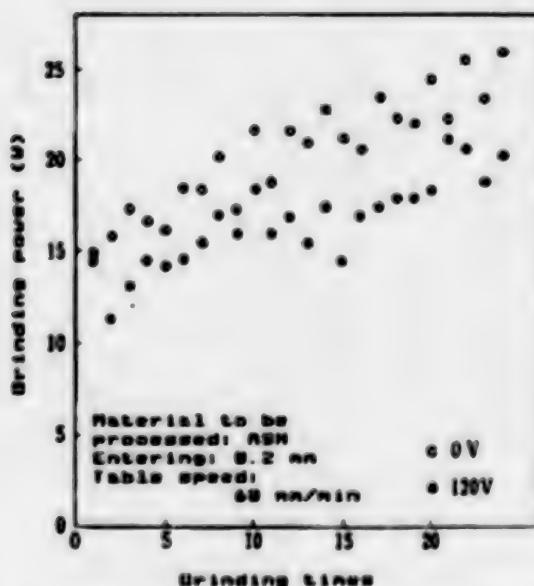


Figure 7. Effect of Discharge on Grinding Power

increase in grinding times is smaller than that when the voltage is not applied. This tendency can be observed when grinding is done about 10 times. At this time, the relationships between the grinding times and the amount of materials removed are almost the same in both cases, as shown in Figure 8, and no remarkable difference can be observed in the amounts of whetstone wear, as shown in Figure 9. In Figure 9, (a) refers to when the grinding processing alone was conducted, while (b) refers to when voltage was applied also. The upper figures show the whetstone profile when grinding was done twice, and the lower figures the profile when grinding was done 24 times.

To study the grinding mechanism of discharge grinding composite processing, experiments were conducted by increasing grinding times. The materials used included a vitrified diamond whetstone with 12 electrodes, each one 1 mm thick, and zirconia 90 mm long. Entering was set at 0.3 mm and the table speed at 240 mm/minute. Grinding was done 48 times for each specimen. Materials were changed every 48 times of grinding, and grinding experiments were continued.

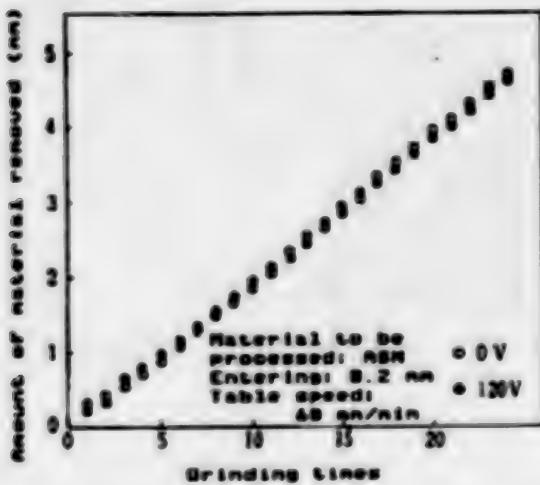


Figure 8. Relationship Between Material Removal Amount and Grinding Times

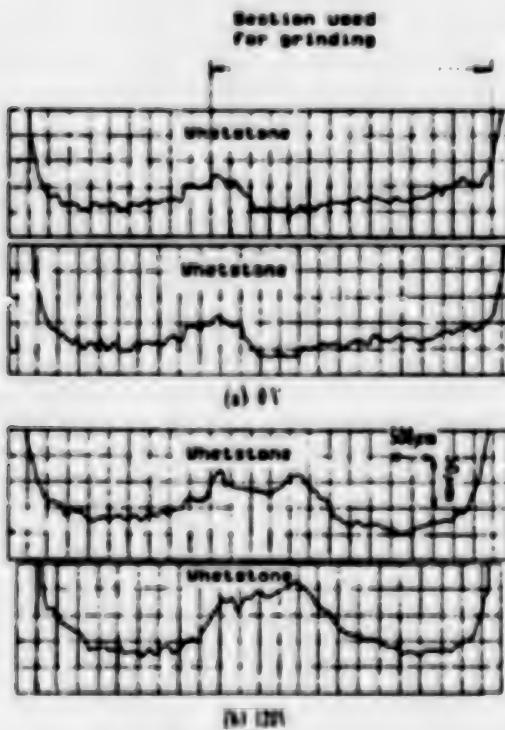


Figure 9. Whetstone Configurations Before and After Grinding

Figure 10 shows changes in the grinding power when grinding was done 108 times without applying voltage, while voltage was applied from the 109th time onward. The changes in the grinding power at the 48th and 96th times were due to the exchange of materials. The grinding power increases as the grinding times increase. The reasons for this increase include whetstone loading and wear. The grinding power falls about 20 W at the time of

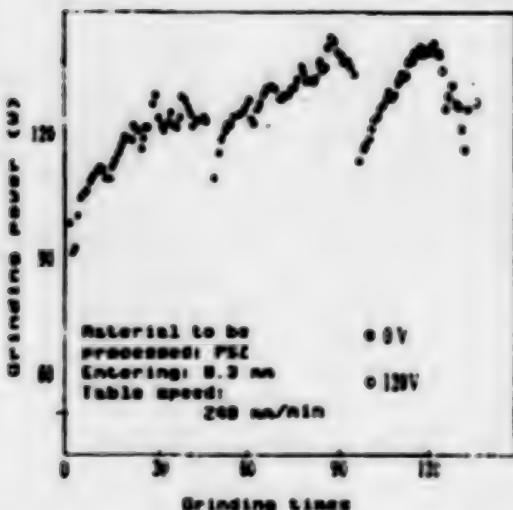


Figure 10. Relationships Between Grinding Times and Grinding Power

material exchange due to a change in the surface conditions of materials to be machined. When 120 V is applied, the grinding power drops quickly after increasing for a while following the voltage application. This is believed to be attributable to the discharge occurring between the whetstone and the material, which relieves the whetstone from loading and sets the abrasive.

Figures 11 and 12 are the results of a study of changes in the whetstone surface. Figure 12 shows the results when voltage was applied. When no voltage was applied, little change was observed in the whetstone surface configuration. When voltage was applied, wear of about 10 μm and 30 μm were observed at the 48th and 96th times, respectively. It is difficult to believe that the wear of 30 μm was due to the falling off of diamonds since the average grain diameter of diamonds was about 80 μm . Therefore, this is considered attributable to the elimination of loading.

Photos 9 and 10 show the relationships between the voltage and current when grinding was done with a whetstone, in which 12 electrodes were embedded, while discharging electricity, and Lissajous' figure. The current changed and discharge occurred every time the electrode passed by the material to be machined. Since the voltage applied was 50 Hz full-wave rectified voltage, the contact-making conditions were recovered immediately following discharge.

5. Conclusion

Arguments have been raised about the effectiveness of the use of electric discharge in the grinding processing of ceramics. However, it is necessary to discuss improvements in processing efficiency and the processing phenomenon separately.

The author has been conducting basic research on how the combined use of electric discharge will change the processing phenomenon in the grinding of ceramics with a diamond whetstone, and discusses it in this article. No

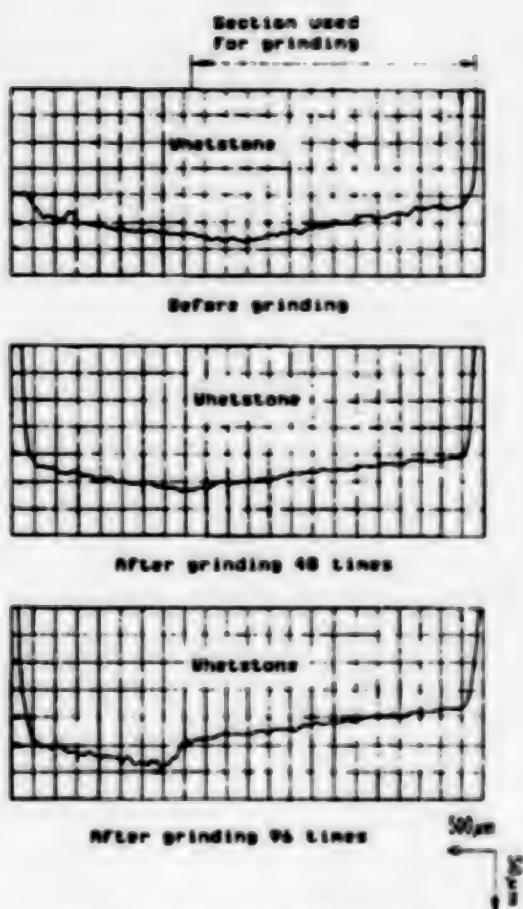


Figure 11. Whetstone Configurations When No Voltage Is Applied

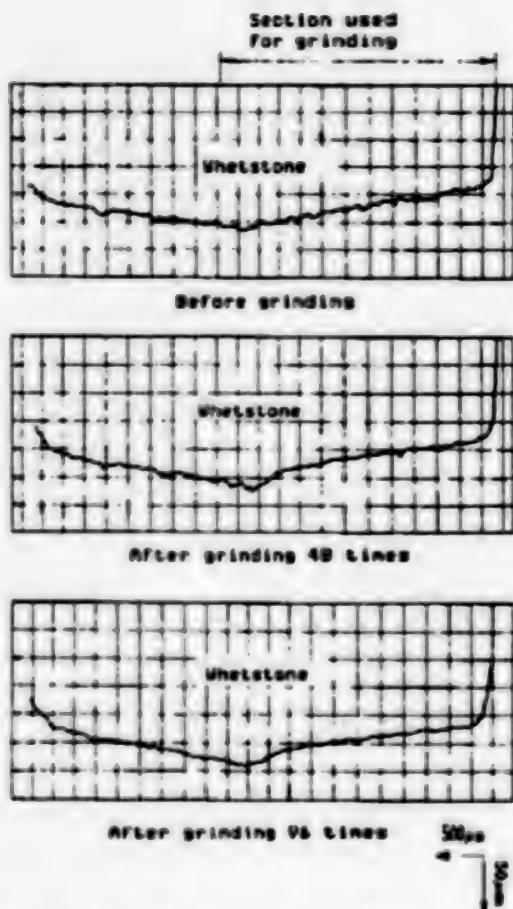


Figure 12. Whetstone Configurations When Voltage Is Applied

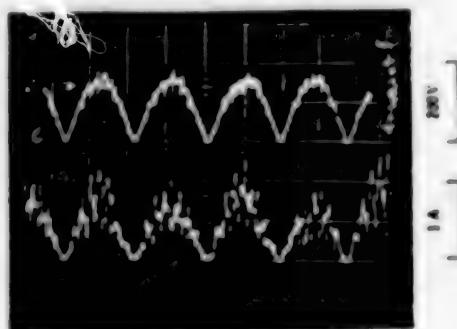


Photo 9. Voltage/Current Patterns
(Above: Voltage; Below: Current)

discussion is made concerning whether or not the combined use of electric discharge is effective in improving processing efficiency. I think it is possible to discuss this only after confirming the mechanism of the processing phenomenon and developing and studying tools and power sources suitable for efficiency improvement. At present, my research has not reached that level.

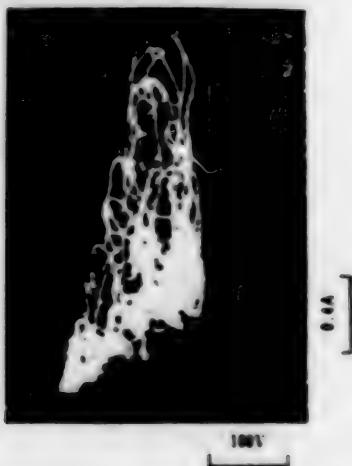


Photo 10. Voltage/Current Lissajous Pattern

It is difficult to explain the mechanism of the processing phenomenon. Systematizing the phenomenon easily and drawing conclusions will mislead thinking in the future. I think we are still at the stage where many experiments are needed regarding the discharge grinding composite processing of ceramics. My research of the matter is still only a tiny part of the study needed, and I do not think I have explained the mechanism. I will be happy if this article is of any help to those who are engaged in the processing of ceramics.

20159/9365

Brittle Material Processing Reported

43064023e Tokyo KIKAI TO KOGU in Japanese Jan 88 pp 48-53

[Article by Koichi Hatano of Shibayama Machinery Corporation]

[Text] 1. Introduction

We are currently faced with a problem involving the processing of new materials, such as fine ceramics and composite materials. These materials have their own old and new histories. They are characterized as materials with super hardness that are extremely difficult to process.

As the reader may already know, the development of a fine ceramic engine has triggered the advancement of the ultrasonic processing method, enabling the processing of ceramics. Our company handles the products of the internationally recognized Branson Sonic Power Inc. The processing technique, examples and machinery will be discussed in this article.

2. Ultrasonic Rotation Processing Method

The following discusses the conventional processing methods applicable to hard and brittle materials. They involve both advantages and disadvantages.

- 1) Grinding and punching methods using a diamond whetstone--during the punching process, burring and/or cracking occurs. The flatness of the surface ground is not very good (Figure 1).
- 2) Ultrasonic impact grinding method--impact grinding by ultrasonic waves requires a grinding or polishing liquid (Figure 2). It is obvious that tools are relatively easily worn. A processed shape becomes tapered, as seen in Figure 3.

The ultrasonic processing machine UMF-7 made by Branson was designed to utilize the advantages of both methods (Figure 4).

The composition of this machine is as follows: A diamond tool is screwed to the tip of an ultrasonic conversion horn, and a converter and a set of tools are supported by bearings. The machine rotates at 5,000 rpm by an electric motor with 1 horsepower. Ultrasonic energy from a power supply is

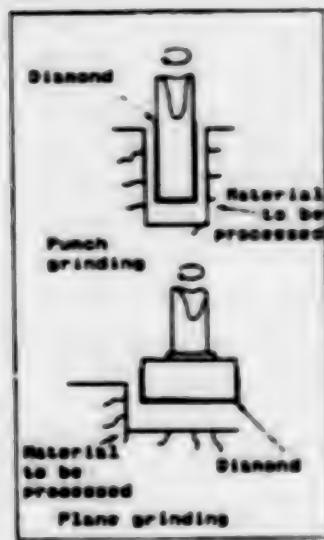


Figure 1. Conventional Processing Method

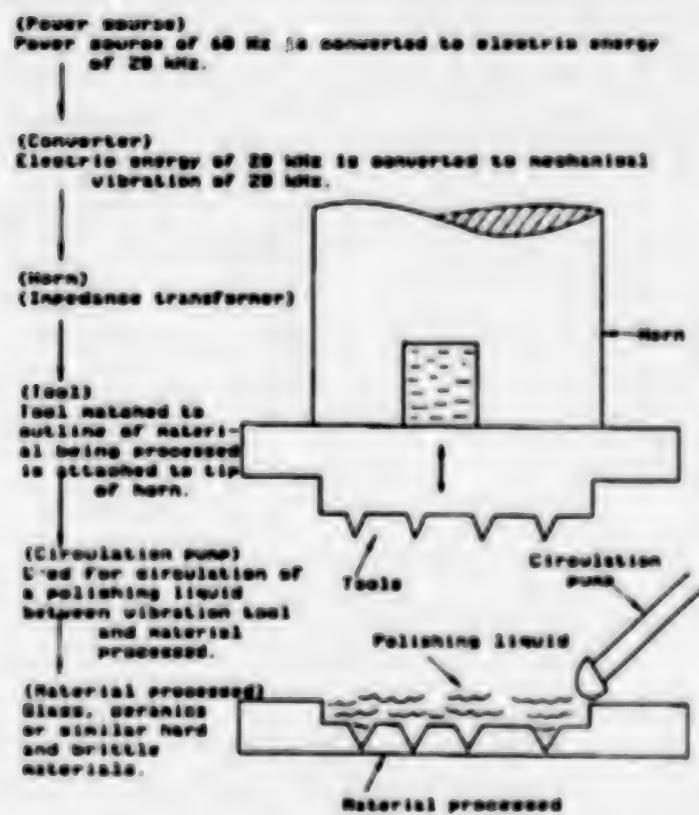


Figure 2. Ultrasonic Impact Grinding Method

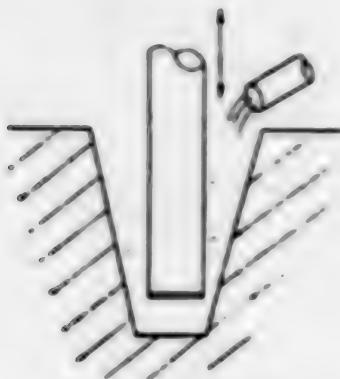


Figure 3. Ultrasonic Impact Grinding Method

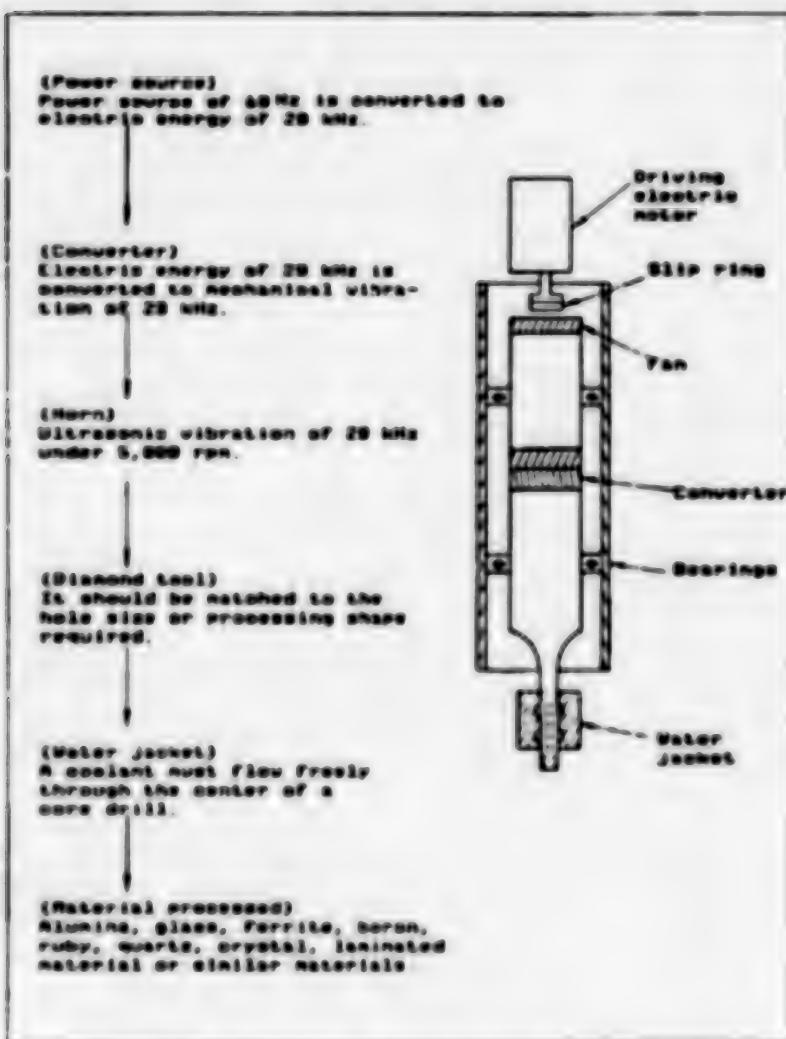


Figure 4. Processing Principle of Ultrasonic Processing Machine Made by Branson

transmitted to a transformer through a carbon brush and a slip ring. Drilling, grooving, plane grinding and screw cutting are possible by utilizing this machine.

(1) Drilling Processing (Figure 5)

A diamond core drill is usually used. A metal-bond diamond whetstone is struck at the tip of a core drill made of steel. A coolant liquid splashes from the center of the tool through the horn of the water jacket.

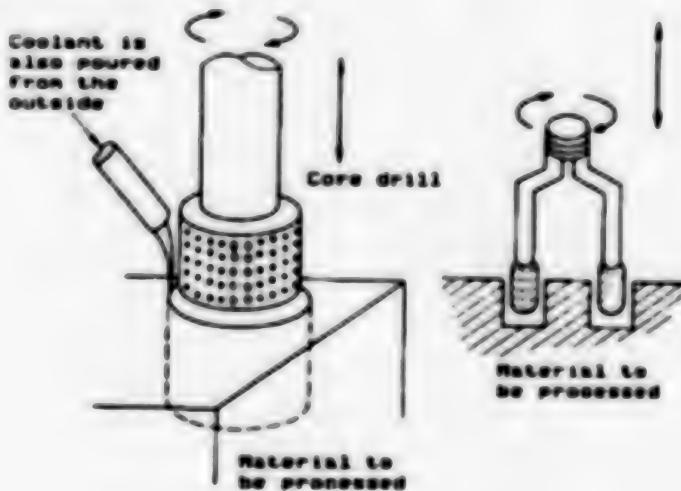


Figure 5. Drilling Processing

The following are advantages obtained when ultrasonic vibration is given to a rotational tool.

- 1) Friction between the tool and materials being processed is reduced.
- 2) Friction through a tool is reduced during punch processing.
- 3) A large amount of coolant is splashed easily since grinding scraps are removed.
- 4) A cleaning effect is seen at the tip of the tool edge by ultrasonic waves.

(2) Plane Grinding (Figure 6)

Grooving and excavation processing can be accomplished with better accuracy than when using an ordinary grinder. The advantages of ultrasonic processing include fast processing and better accuracy on the surface processed.

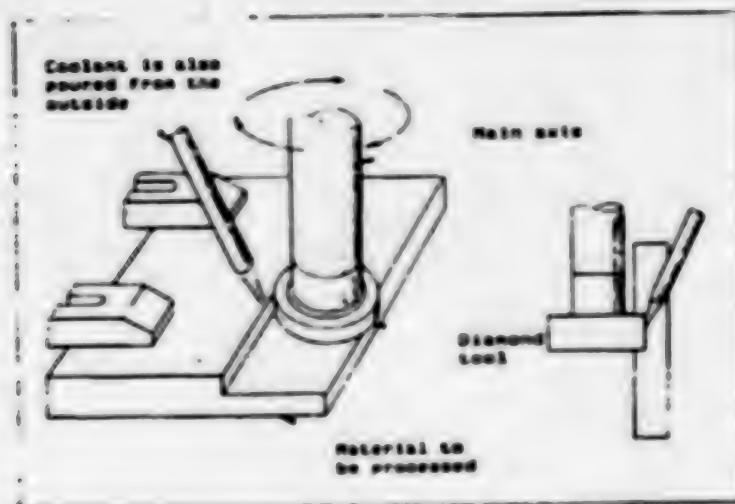


Figure 6. Plane Grinding

(3) Screw Machining

Screw machining requires a rotational fastener. It is preferable to have a motor-driven type fastener which rotates slowly at the maximum speed of 4 rpm. A leading screw is connected to the fastener, and the screw pitch is controlled by the speed of rotation and driving. When a different screw is processed, another leading screw has to be used. This fastener is bolted on an X-Y table, the material to be processed is fixed by the fastener, and then the processing takes place.

(a) UMT female screw machining (Figure 7)

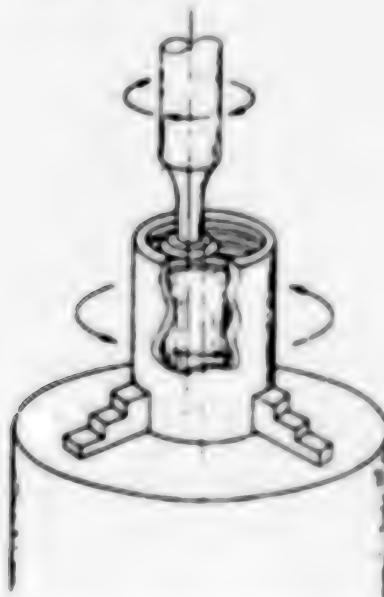


Figure 7. Female Screw Machining Process

A horn fixed at a head which works only for ultrasonic waves rotates at 2,000 through 5,000 rpm. A tool axis rotates under eccentric motion, similar to that of male screwing. The size of the tool must be smaller than the diameter of the material to be processed. The diameter of the diamond whetstone must be 3/32 of an inch larger than that of the tool shank, and the ultrasonic processing pressure is reduced.

(b) UMT male screw machining (Figure 8)

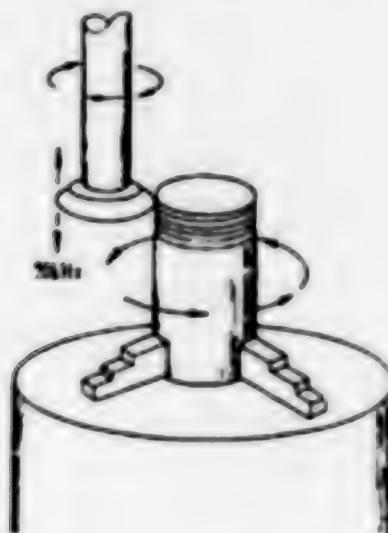


Figure 8. Male Screw Machining Process

A horn is fixed to a head which does not move except under ultrasonic vibration. It rotates at 2,000 to 5,000 rpm. The depth of a screw is determined by how much the material being processed can move toward the tool. A rotation fastener connected to a leading screw rotates slowly at 0 to 4 rpm, and the screwing processing takes place. The angle of the edge of a tool is usually 55 or 60 degrees. Generally speaking, screw processing is not applicable to ceramics. However, it is possible utilizing the UMT-7.

3. Processing Examples

(1) Deep Punch Processing on Glass Materials (Photo 2 [not reproduced])

Two holes with a diameter of 0.004 inch are made of a lump of glass. The degree of perpendicularity of the holes is worth noting. The processing time is about 2 minutes for each hole (the degree of perpendicularity is to affected by the processing time).

(2) Drill Processing for Ruby and Sapphire (Bar used for laser) (Photo 3 [not reproduced])

A straight hole with a diameter of 3 mm is processed on a ruby bar 100 mm in length and with a diameter of 13 mm. It takes about 16 minutes for this

processing. It is possible to place holes with diameters of 3 mm and 1.5 mm on a sapphire disk with a thickness of 3 mm under the average speed of 12 seconds per hole.

(3) Excavation of Alumina Ceramics (Photo 4 [not reproduced])

A disk with a diameter of one-half inch is cut out by a core drill. Holes 1 mm in diameter have already been placed on the material with a thickness of only 0.38 mm.

(4) Drill Processing for Alumina Ceramics (Photo 5 [not reproduced])

Punch processing is applied to alumina 0.5 mm in thickness. The processing time is from 5 to 15 seconds.

(5) Shaving and Punching for Ferrite (Photo 6 [not reproduced])

A ferrite cube shaved from a lump is shown. All surfaces are processed by the UMT-7, and a hole one-fourth inch in diameter is made.

(6) Grooving of Glass (Photo 7 [not reproduced])

A groove 6.3 x 6.3 mm is made by mill processing on a lump of glass. The groove processing time totals 45 minutes. The occurrence of chipping is well suppressed.

(7) Screwing of Ceramics (Photo 8 [not reproduced])

A ceramic bolt and nut processed by the UMT-7 is shown.

(8) Typical Processing Example Utilizing UMT-6 (Photo 9 [not reproduced])

This is a drill processing example (note that a partition is very thin). A male screw, a female screw, and other mill processing examples are seen.

(9) Processing Example of Alumina (Photo 10 [not reproduced])

This shows an example in which punching is made on alumina oxide ceramics by the UMT-7, and then the screw processing is applied.

4. Various Kinds of Processing Machines

Our company is joining in a technical tie-up with Branson Sonic Power Inc., and is a manufacturer and seller of CNC-controlled ultrasonic rotary processing machines. Various kinds of machines are available depending upon their usage and application requirements.

Photo 11 [not reproduced] shows the one-axis CNC standard machine. Photo 12 [not reproduced] shows the CNC machine for deep punch processing.

As the next example, the mechanism by which a deep hole is actually processed on a quartz glass bar used for optical fibers is explained.

First of all, as shown in Photo 14 [not reproduced], preliminary punch processing is conducted by a 1-inch long diamond tool. For the next step, as shown in Photo 15 [not reproduced], another diamond tool with a long shank is applied to make a long hole. Photo 16 [not reproduced] presents an example of a quartz glass bar used for optical fibers processed by the above steps.

In addition, the UMT-7 can be utilized for processing a laser gyroscope, as shown in Figure 9. Usually, three long holes 1.5 mm in diameter are made. Zerodure is used as the material, and a very high degree of perpendicularity of the hole is demanded. This can be accomplished by using the UMT-7.

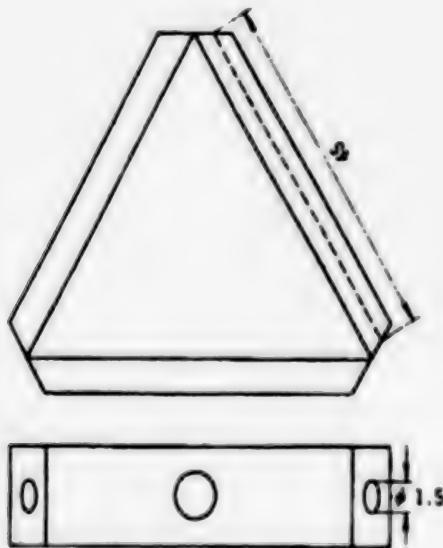


Figure 9. Laser Gyroscope

<UMT Air-Spindle>

As seen in Figure 10 [not reproduced], the spindle made by Branson is supported by two sets of bearings. In order to suppress vibration in the radial direction, it is surrounded by plastics. Due to the flexibility of the plastics, rotational accuracy is sacrificed. Therefore, the accuracy is 0.001 inch.

For this reason, our company does not use mechanical bearings. Instead, the spindle is supported by air pressure (Figure 10). As a result, the accuracy reaches the order of 1 to 2 μm . A highly accurate laser gyroscope and the manufacturing of optical fibers have become possible due to this improvement. Photo 17 [not reproduced] shows the exterior view of the air spindle. Photos 18 and 19 [not reproduced] show the actual measurement of ultrasonic waves.

Photo 20 [not reproduced] shows the latest three-axis CNC control machine developed by our company. Photo 21 [not reproduced] shows the diamond tool made by Branson, which is applied to this three-axis CNC control machine.

Due to the successful development of the air spindle, various kinds of ultrasonic machines are being designed by our company. We are convinced that our machines will contribute greatly to the processing of hard and brittle materials, such as ceramics.

20149/9365

Use of Cataphoresis Effects Discussed

43064023f Tokyo KIKAI TO KOGU in Japanese Jan 88 pp 54-60

[Article by Toshiji Kurobe, Department of Industrial Precision Engineering, Kanazawa University]

[Text] 1. Introduction

With the appearance of information machines and precision devices, higher processing accuracy of machinery parts accompanying such machines and devices has been strongly demanded. Sometimes processing accuracy on the submicron order is demanded. In the case of materials used for electronic parts, not only must the geometric configurations, such as shape accuracy and surface accuracy, be perfect, but also the creation of an almost perfect face from a crystallographic viewpoint is demanded. In order to respond to diversified needs for the present processing techniques, processing methods free from traditional approaches originating from new ideas are being pursued more and more.

In this paper, among electric and magnetic field-assisted fine finishing techniques, a "finishing technique utilizing a cataphoresis phenomenon" which claims an electric field is going to be discussed. The finishing method utilizing "a field" is characterized by the finishing processing that can be electromagnetically controlled, and finishing processing for free surfaces is possible to a certain extent.

2. What is Cataphoresis

2.1 Interfacial Electrodynamic Phenomenon

When two different phases come into contact, generally the separation of positive and negative charges at the interface occurs, and a difference in electric potential is generated between the two phases. The system in which positive and negative electricity coexist is called interfacial two-layer electricity.

Two-layer electricity also exists around particles dispersed in a liquid. When an electric field is applied parallel to the interface, the direction of the electric force exerted to phases composed of the interfaces reverses since the electric charge at both sides of the interface is reversed. As a

result, the relative motion of these phases occurs. This is called an interface electrokinetic phenomenon. This phenomenon can be roughly classified into electroendosmosis, streaming potential, migration potential, and cataphoresis. Among these, when an electric field is applied to a colloid particle system, the phenomenon involving which particles move around is called cataphoresis. This is similar to the ion motion in an electric field.

The causes of the electrification of colloid particles migrating in a liquid can be roughly divided into three categories. In the first case, when the permittivities of the colloid particles and a solvent differ, the one having the larger permittivity is positively electrified. In the second one, due to absorption, the colloid particles are electrified by absorbing ions. In the third one, the material itself, which is composed of colloid particles, is electrified through ionization.

When a solid and a liquid move around relatively at their interface, a thin layer right next to the surface of the solid moves along with the solid if the liquid layer sticks to the solid surface. A boundary layer between the fixed liquid layer and the moving liquid is called a slide face. The difference in electric potential between the slide face and the internal portion of the liquid is called ζ electric potential or interface moving electric potential. ζ electric potential is recognized as a very important quantity which rules the electrokinetic phenomenon of an interface.

2.2 Measurement of Speed of cataphoresis

It is possible to measure the speed of cataphoresis by the dynamic interface method. As shown in Figure 1, a colloid or suspension is put into a U-shaped tube. A change in the surface of the liquid after cataphoresis takes place is read by an instrument, such as a microscope. The intensity of the electric field E is V/L , where L is the distance between both electrodes, and V is the difference in electric potential. When the moving distance of an interface is $2l$, $V = l/t$ (V : migration speed, t : time). Accordingly, ζ electric potential can be expressed by equation (1).

$$\zeta = \frac{\mu l}{t \epsilon V} \quad (1)$$

where, μ and ϵ are the viscosity of a solvent and permittivity, respectively.

Figure 2 shows the relationship between electrical potential of both electrodes (V) and the moving distance of an interface ($2l$) for colloidal silica SiO_2 ($0.02 \mu\text{m}$). The solvent is water and the constant measurement time is 30 minutes. The result of this measurement indicates that a cataphoresis phenomenon exists for particles and that this phenomenon can be utilized for processing.

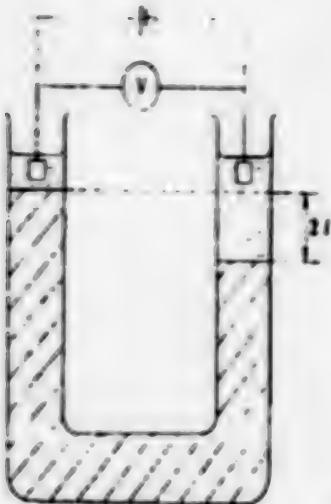


Figure 1. Principle of Measuring Electric Potential

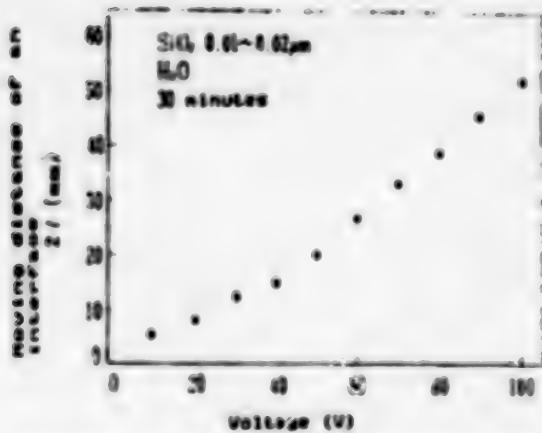


Figure 2. Relationship Between Electrical Potential of Electrodes and Moving Distance of an Interface

2.3 Processing Principle

As described in section 2.1 above, two electric layers are generated on the surfaces of solid particles dispersed in a liquid. There are several causes for the generation of the layers. In the case of an oxidized particle suspended in water, a hydrate generated on the surface is ionized, and an ion with a large affinity to a particle is absorbed on the surface of the particle. Through this process, two layer electricity occurs. Figure 3 shows the above as it relates to (1) silica (SiO_2) and (2) alumina (Al_2O_3).

It is known that a particle with a radius of a dispersed in a liquid has an electric charge $Q = \epsilon \pi r^2 \zeta$, where ϵ and ζ are the permittivity and ζ electric potential of a liquid, respectively. Two methods are used to control the motion of a particle utilizing the electric nature of a particle migrated in a liquid. It is assumed that the particle is negatively electrified.

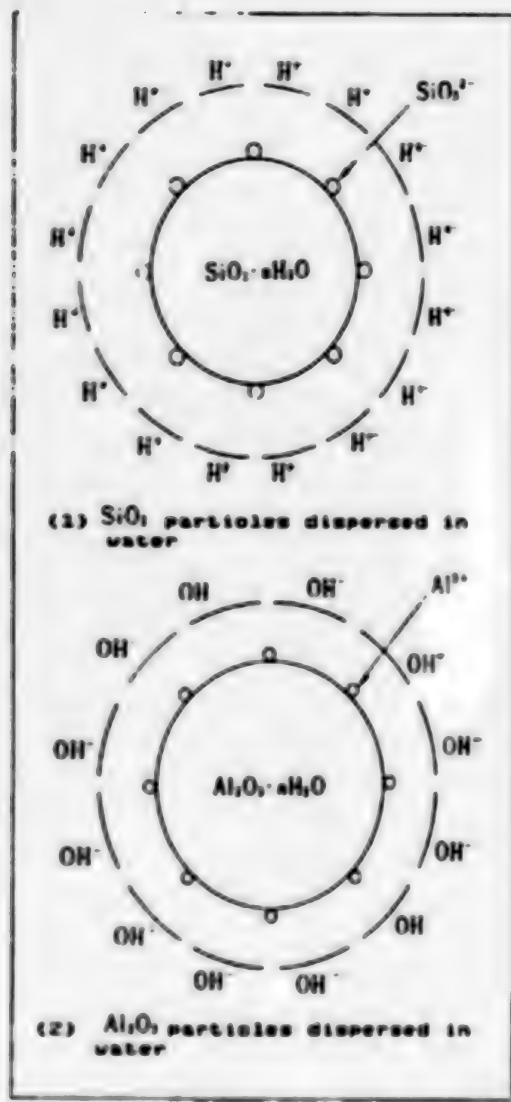


Figure 3. Electrification Mechanism of Fine Grinding Particles

(1) Method to capture particles on a processing surface

As shown in Figure 4, when a direct current is impressed so that the processing surface has a positive charge and the tool surface has a negative one, the particle starts to move under force directed toward the processing direction. This velocity is calculated by $V_g = \epsilon \cdot E / \mu$, where E is the intensity of the electric field. Accordingly, the kinematic energy of a particle exerted on the processing surface increases as the impressed voltage becomes larger.

(2) Method to accumulate particles on a tool's surface

As shown in Figure 5, when direct current is impressed so that the tool surface has a positive charge and the processing surface or their electrode had a negative one, opposite to the case described in (1), particles are accumulated on the tool surface through force exerted toward it. As a

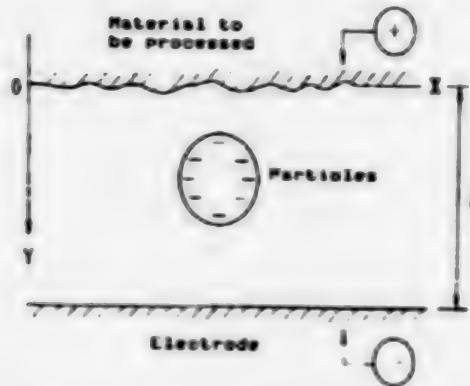


Figure 4. Processing Principle (Model 1)

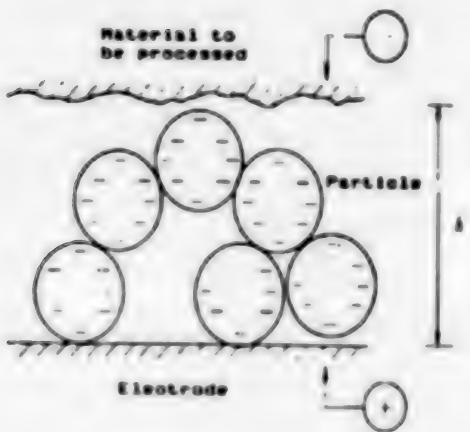


Figure 5. Processing Principle (Model 2)

result, friction force between the particles and the tool surface is generated, and the particles move with almost the same speed as that of the tool's surface. Then, energy proportional to the impressed voltage is given to the processing surface.

3. Surface Finishing

3.1 Finishing the Presence of a Clearance

(1) Finishing machine and processing conditions

The schematic diagram of a cataphoresis finishing device is shown in Figure 6. The processing device (I) uses the method which directly impresses direct current to the materials to be processed. On the other hand, the processing device (II) is based on the method which impresses direct current between an electrode and the tool surface under the condition in which an electrode is separated from the materials to be processed. Both devices have a tool surface of 80 mm in outer diameter, and an eccentric distance of upper and lower rotation axes of 22 mm. The tool surface consists of brass. An adjustment of the clearance between the processed

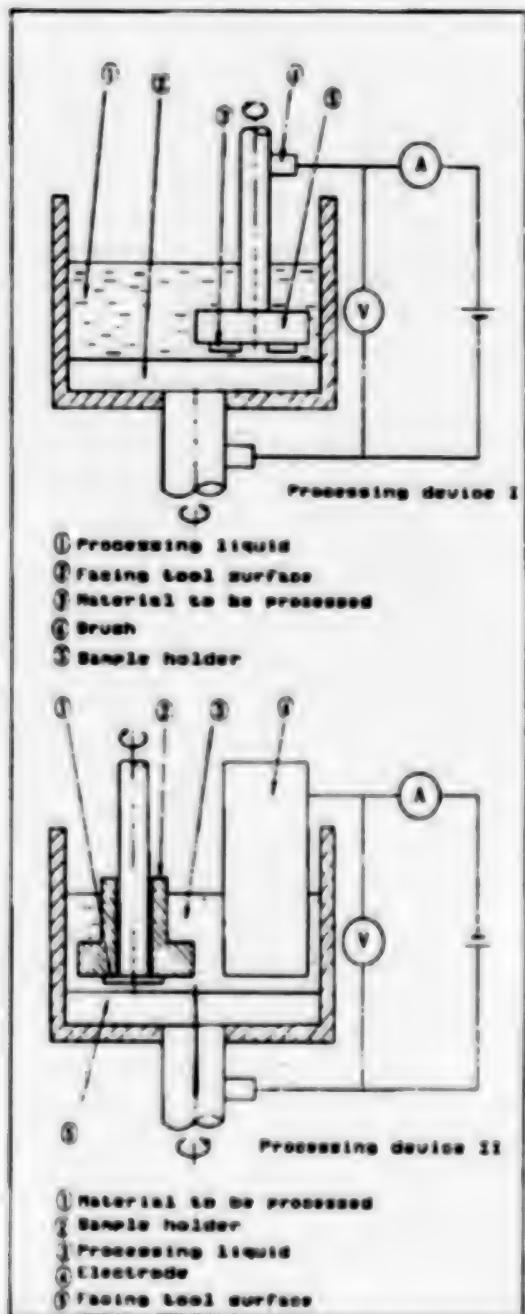


Figure 6. Schematic Diagram of Finishing Device

surface and the tool surface is done by a vertical motion of the upper rotation axis. The detection and adjustment of the clearance are actually carried out by using a dial-gauge.

In the case of the processing device (I) shown in Figure 6, a sample holder is placed directly on the upper rotation axis. Voltage is impressed so that the tool surface has a positive charge, and the processed material has a negative one. For a comparison, measurement was also made of the

opposite case. In device (II), the processed material is fixed by the holder made of acrylic, which floats on the processing liquid due to its buoyant force.

Alumina (particle diameters of 20-0.2 μm) and silica (particle diameters of 10-0.02 μm) were used for grinding particles. This was to investigate the difference in the amount of electrification between different grinding particles. Distilled water, ethyl alcohol and methyl alcohol were used as solvents. Regarding processed materials, carbon steel and silicon single crystal wafers were applied to the processing devices (I) and (II), respectively. Table 1 shows the processing conditions.

Table 1. Processing Conditions

	Device I	Device II
Samples	S 45 C	Si
Number of rotations of sample holder	1,100 rpm	300 rpm
Number of rotations of polisher	100 rpm	100 rpm
Preprocessing	#0 emery paper	$\text{Al}_2\text{O}_3 \approx 2,000$ lapping
Sample dimensions	67.7 x 7 (mm)	20 x 20 x 0.8 (mm)
Clearance	20-40 μm	5-30 μm

(2) Measurement results and discussion

The measurement results of device (I) are shown in Figure 7. Measurements were conducted under three different impressed voltages, 1.5 V, 0 V, and -1.5 V. An impressed voltage of 1.5 V means that the processed material has a positive charge and the tool surface has a negative one, while -1.5 V indicates the opposite case. The processing liquid is ethyl alcohol mixed with silica (particle diameters less than 10 μm) with a bulk density of 4 percent. Figure 7 shows the relationship between the processing time and the amount of material processed. From this figure, it can be seen that the amount of the material processed increases in proportion to the processing time. The largest gradient of a plotted straight line is obtained when the impressed voltage is 1.5 V. It is believed that the fact that the amount of material processed increases when the voltage is impressed is due not only to the elimination effect by the impact of particles, but also to the increase in the number of particles which come to the processed surface one after another.

Measurement results of device (II) are indicated in Figures 8 and 9. As the processing liquid, ethyl alcohol suspended by alumina particles

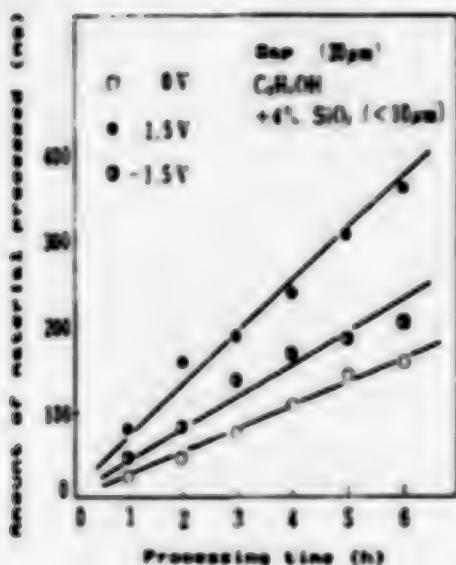


Figure 7. Relationship Between Amount of Material Processed and Processing Time

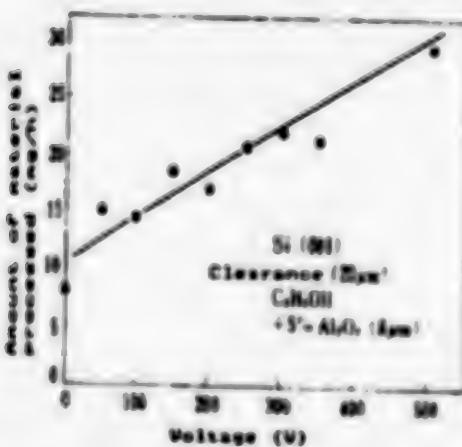


Figure 8. Relationship Between Voltage and Amount of Material Processed

(particle diameter of 8 μm) with a density of 5 percent was used. Figure 8 shows the relationship between the voltage and the amount of material processed. From this figure, it is seen that as the voltage increases, the amount of material processed increases linearly. Figure 9 shows the results of the influence of the electric current on processing. The processing liquid is composed of distilled water suspended by alumina particles 5 percent with a bulk density of 5 percent. As seen from the figure, as the electric current increases, the amount of material processed increases linearly.

Figure 10 shows the relationship between the impressed voltage and surface roughness R_{max} when silica is used as the grinding particle. As seen from

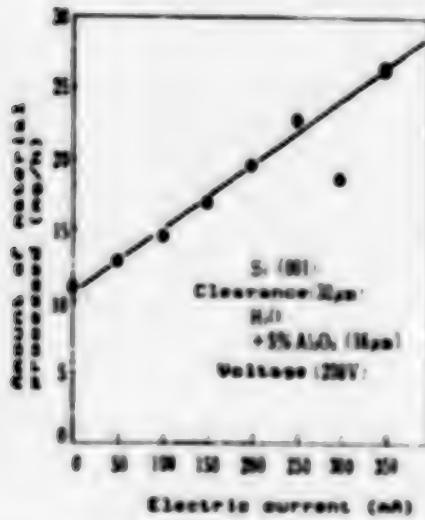


Figure 9. Relationship Between Amount of Material Processed and Electric Current

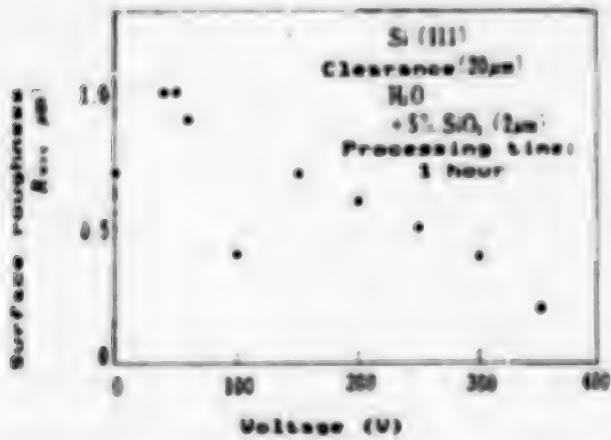


Figure 10. Relationship Between Voltage and Surface Roughness

the figure, surface roughness becomes larger as the impressed voltage increases, but when it reaches the extremum, it gradually decreases. This aspect was observed through a picture taken by a microscope, which is shown in Photo 1. In the region where a small voltage is applied, a surface imposing lapping is observed. When the voltage becomes larger, a polished surface appears. The surface roughness of the material R_{zav} is $1.2 \mu\text{m}$.

From the above measurements, it is obvious that surface finishing utilizing the cataphoresis phenomenon of grinding particles is possible. A discussion of the measurement results follows.

First, when the measurement results (Figure 7) of device (I) are looked at, the amount of material processed becomes the largest under an impressed voltage of 1.5 V. In the case in which a non-water solution, such as ethyl alcohol, is used as a processing liquid, grinding particles are thought to

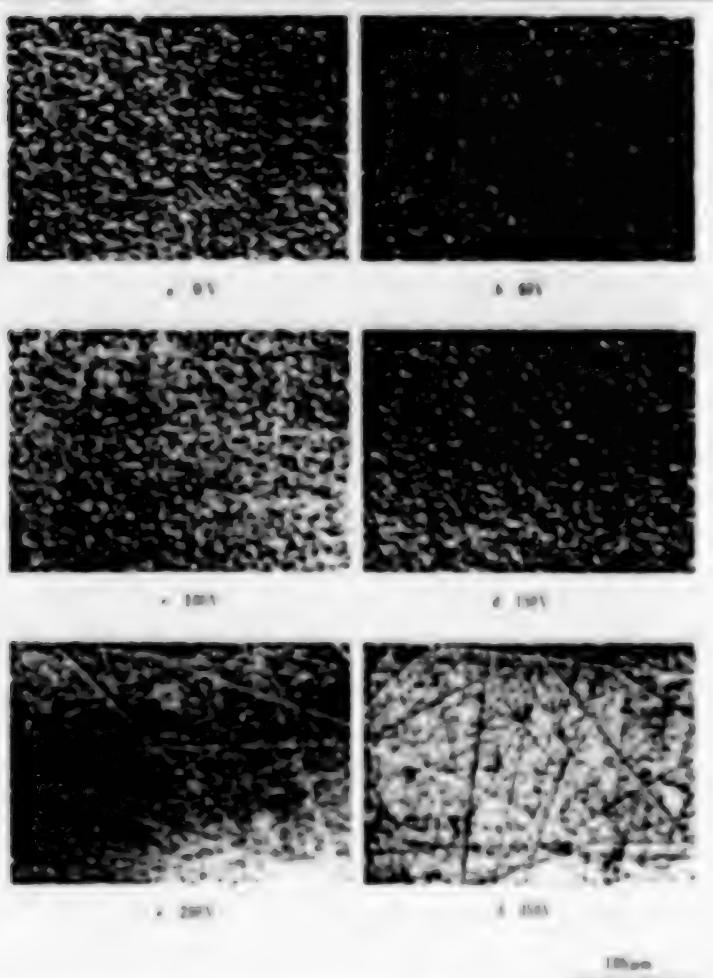


Photo 1. Microscopic Photos of Processed Surface

be negatively electrified. Therefore, in the case in which the specific gravity of grinding particles is small or a clearance between the processed surface and the tool surface is relatively narrow, the method in which grinding particles are captured on the processed surface is more advantageous than the one in which they are accumulated on the tool surface. On the other hand, when a clearance is wide and the specific gravity of the grinding particles is large, it is believed that the method accumulating grinding particles on the tool surface is advantageous.

When water is used as the processing liquid in device (II), shown in Figure 9, the amount of material processed increases as the electric current becomes larger. This is due to the fact that, since water is a strong electrolyte, grinding particles dispersed in water are ionized. Therefore, the increase in the electric current leads to the accumulation of grinding particles on the facing tool surface. This results in an increase in the amount of material processed.

On the other hand, when ethyl alcohol is used as the processing liquid, almost no electric current passes through due to the small electrolytic dissociation. The measurement results for device (II) (Figure 8) indicate that, as the impressed voltage increases, the amount of material processed becomes large. This is because the force generated during the accumulation of grinding particles on the facing tool surface is proportional to the intensity of the electric field, i.e., the magnitude of the impressed voltage.

Following is a discussion involving the picture taken by a microscope shown in Photo 1. When the voltage is relatively low, e.g., in the range of 0 to 150 V, electric coherence between the facing tool surface and grinding particles is weak, and the number of grinding particles accumulated is small. It is assumed that grinding particles carry out processing under rotational motion, i.e., the processed surface is believed to become a lapping surface. However, as the impressed voltage becomes larger, e.g., 200 to 350 V, the electric coherence between the facing tool surface and grinding particles becomes strong, and the number of accumulated grinding particles becomes large. As a result, the grinding particles start to carry out scratching processing. Therefore, the processed surface becomes polished.

3.2 Finishing in the Case of No Clearance

(1) Finishing device and processing conditions

The new device was designed to accomplish contact finishing through the addition of a load. The schematic diagram of the newly-developed finishing device is shown in Figure 11. The device is composed of a finishing tub, a specimen holding tool and a power source. The finishing tub is constructed so that a side wall made of polyvinyl chloride is placed on a stainless steel disk (outer diameter 196 mm) covered by a polisher. An abradant made from suspended grinding particles is put into the tub. The stainless steel disk is fixed to the steel rotation disk bored largely at the central portion. Tap water passes through the bored portion. This prevents the temperature of the polishing liquid to increase through processing.

The material to be processed is placed at the lower end of the upper rotation axis which moves up and down smoothly through linear ball bearings, and also is demountable if desired. Since the dead load of the axis is compensated for by the coil spring, it is not exerted as processing pressure. Polishing pressure is given by adding the dead load to the rotation axis.

An eccentric distance between the upper rotation axis and the lower surface table is 67 mm. A stainless steel electrode plate (width: 37 mm, thickness: 7 mm, fan shape with vertical angle of 60 degrees) was prepared. It functioned as the upper electrode. It was placed (immersed in a liquid) near the upper rotation axis. Voltage was impressed between the fan-shaped electrode and the finishing tub stainless steel rotation disk (lower electrode). The distance between the electrodes was 5.5 mm.

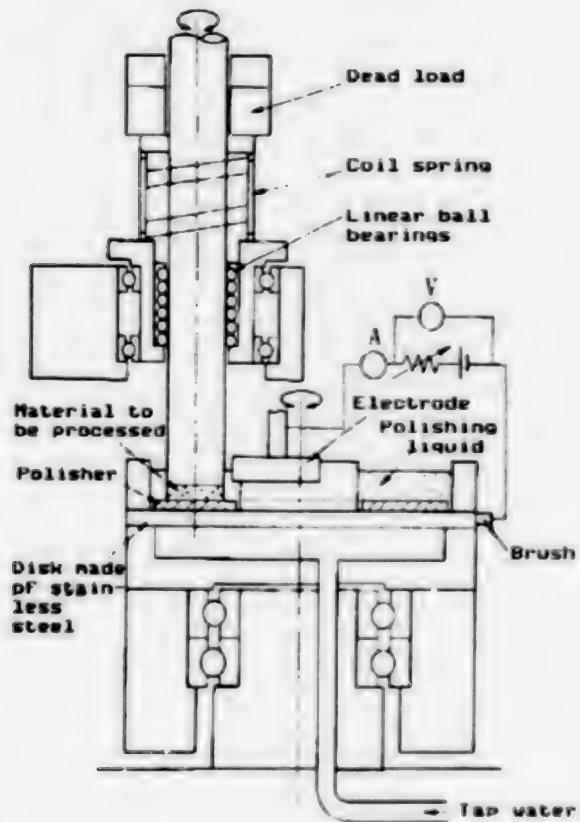


Figure 11. Pressure-Given-Type Finishing Device

The material processed is silicon nitride of □ 9 x thickness of 2 mm. A finishing test was conducted by sticking three samples on a glass plate (Φ25 mm) at regular intervals of 120 degrees, and then installing them on the upper rotation axis. A non-woven polisher was used. Colcothar (Fe_2O_3) was used as the grinding particle.

(2) Measurement results and discussion

Figure 12 shows the measurement results. It shows the relationship between the amount of material processed and the impressed voltage. The measurements took place under the following conditions: processing time: 15 minutes, processing pressure: 4×10^4 Pa, processing speed: 8.4 m/min, grinding particle density: 0.18 volume percent (dispersion solvent: water). In this figure, NonF indicates that the voltage was not impressed, FU + means that the grinding particles were forced to move toward the upper electrode, and FD (+) refers to the grinding particles being forced to move toward the polisher side. From this figure, it can be seen that the amount of material processed increased when the grinding particles migrated upward and voltage exceeded 300 V.

Figure 13 shows the relationship between the amount of material processed and the processing time. From the figure, it can be seen that when the

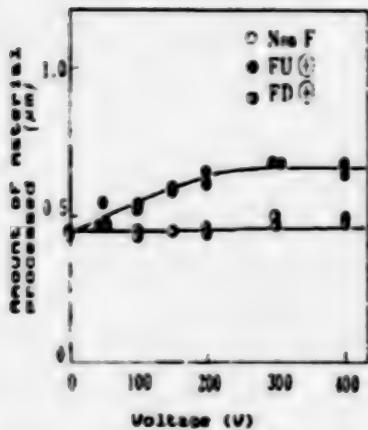


Figure 12. Relationship Between Amount of Material Processed and Voltage

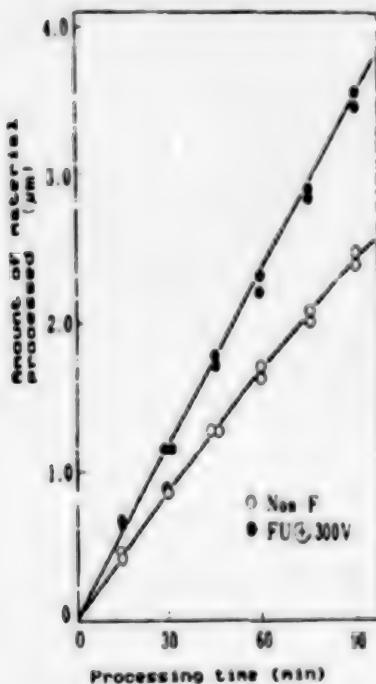


Figure 13. Relationship Between Amount of Material Processed and Processing Time

voltage is impressed, the amount of material processed increases in proportion to the processing time, and the difference in the amount of material processed between the presence of impressed voltage and lack thereof becomes larger as the processing time increases. Figure 14 shows the relationship between the surface roughness (R_z) and processing time. The surface roughness decreases suddenly during the initial stage of processing and, after that, it gradually decreases as the processing time passes. The degree of the sudden decrease in surface roughness has been observed to be larger for materials impressed by voltage than for those when no impressed voltage is applied.

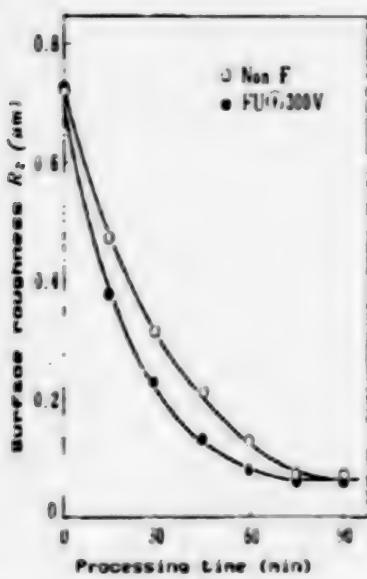


Figure 14. Relationship Between Surface Roughness and Processing Time

Figure 15 shows the relationship between the amount of material processed and the processing pressure. The figure indicates that, as the processing pressure increases, the amount of material processed increases linearly. The amount of material processed becomes larger when the grinding particles migrate upward. In addition, through other experiments in which the grinding particle concentration was changed, in all cases the presence of impressed voltage resulted in a large amount of material processed.

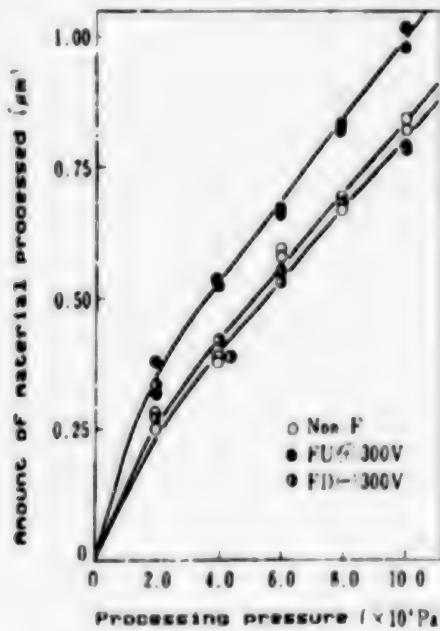


Figure 15. Relationship Between Amount of Material Processed and Processing Pressure

From the above measurements, it has been confirmed that cataphoresis had a positive effect on finishing in the presence of processing pressure. If various resources are available for the structural design of electrodes and the selection of processing liquids, better effects can be accomplished.

4. Conclusion

The possibility of surface finishing utilizing a cataphoresis phenomenon as seen from grinding particles dispersed in a liquid has become apparent. This processing method can electrically control the motion of grinding particles. However, this finishing method was just born and is still at the stage where many possibilities exist. Because of the limited space in this article, it is not mentioned here, but the pH number of a liquid has been confirmed to be one of the variables.

Finishing by utilizing a cataphoresis phenomenon is the finishing method composed of mechanical, chemical, and electronic phenomena. Following the study conducted by the author, research involving cataphoresis finishing was conducted from other viewpoints. The author is eagerly anticipating that the finishing methods utilizing the cataphoresis phenomenon be pursued from various standpoints, and be put to practical use as soon as possible.

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Ultrasonic Vibration Method Discussed

43064023g Tokyo KIKAI TO KOGU in Japanese Jan 88 pp 61-65

[Article by Nagao Saito, Toyota Institute of Technology: "Electric Discharge Processing Utilizing Ultrasonic Vibration"]

[Text] 1. Introduction

Electric discharge processing utilizing ultrasonic vibration was begun around 1957 by Nishimura, et al., and it has been determined that the amount of discharge can be increased by decreasing the discharge resistance R in the condenser discharge, resulting in improved processing speed.

Note) $f = k \cdot \frac{1}{CR}$

When: C - condenser electrostatic capacity (μF)
R - discharge resistance (Ω)
f - amount of discharge (Hz/s)

However, it has not yet been applied to actual electric discharge processing machines. The reasons for this include the following:

- 1) The problems and high cost involved in installing the ultrasonic vibration device.
- 2) It is technically difficult to tune the resonance frequency of the vibration system when equipped with the electrode, and to track according to the electrode consumption.
- 3) The process efficiency could be improved to the required level through proper control of process liquid flow and the periodic vertical motion of the electrode without applying ultrasonic vibration.

∴ is believed that the above comprises the relevant background.

On the other hand, at present very fine processed surfaces (e.g., a processed surface whose roughness, R_{\max} , is smaller than 1 μm) are being pursued, in comparison to those in the past and, since this processing speed is very slow, methods to obtain faster processing speeds are being sought.

The author and others are attempting to use ultrasonic vibration again as a way of improving this processing speed.

The things different from earlier days are that a) the tracking of the resonance frequency is not as difficult because the finishing amount is small, due to its being a finishing processing, and the electrode consumption is very small if $R_{max} = 1 \mu\text{m}$, as mentioned above; b) it was believed that the tracking of the resonance frequency was possible without changing the electrode if it involved electrode low-consumption processing, even if it was a rough or medium-degree processing; c) the handling and control have been facilitated because the vibration efficiency has been improved by the use of the piezoelectric element instead of the magnetostrictive vibrator used previously, in addition to the progress in the peripheral technology, etc.

The following research was started believing industrially meaningful results could be obtained if effective results, i.e., the electric discharge processing of the finishing surface R_{max} of under $1 \mu\text{m}$, were achieved.

2. Research Aims, Test Device, and Test Results

Since the aim is the improvement of the processing efficiency of the finishing surface to $R_{max} = 1 \mu\text{m}$, the following electric condition was selected in order to obtain the best roughness of the processing machine used.

$$I_p = 1(\text{A}), \tau_p = 2(\mu\text{s}), \tau_r = 2 (\mu\text{s})$$

A direct current of about 300 V was piled up to further extend the distance between the electrodes.

The workpiece is the SKH-51, the diameter of the electrode copper material is 15 mm (solid), the polarity of the electrode is (-), and the processing liquid is in the pouring condition.

2.1 Test Device and Test Method

Figure 1 shows the processing device used in this test. The main shaft of the discharge processing machine is equipped with an ultrasonic vibrator and an amplitude expansion horn to extend ultrasonic vibration (resonance frequency 20 kHz) to the electrode.

The measurement of the processing depth against the processing time and the observation of the surface profile were conducted to compare the normal electric discharge processing and the ultrasonic electric discharge processing in the finishing processing condition by changing the size of the amplitude of the electrode ultrasonic vibration and the electrode descending time (T_p) in the discharge stabilization action. The processing depth and the surface roughness are measured on the machine using the tracer-type surface roughness measuring instrument.

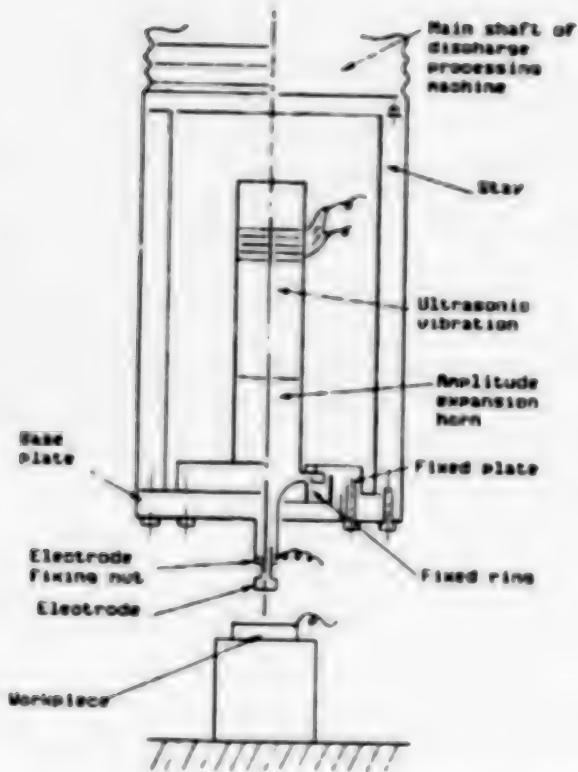


Figure 1. Composition of Processing Device

The ultrasonic vibration involved is observed in addition to the monitoring of the vibration and current between electrodes during the processing in order to observe the processing phenomenon of ultrasonic electric discharge processing.

2.2 Test Results

(1) Electric discharge electrode vertical motion and ultrasonic adding and processing efficiency

In electric discharge processing, the electrode periodic lifting method is used to stabilize the processing by changing the processing liquid between electrodes, moving the electrode up and down periodically. The time during the processing with electricity when the electrode is lowered is expressed by T_d , is not conducted and the electrode is lifted is expressed by T_u . It is desirable if T_d is made large and T_u small, but if it becomes $R_{max} = 1 \mu m$, a long T_d cannot be taken. If one tries to make T_d long, the processed product is accumulated in the very narrow space between electrodes (Note: Distance between electrodes is about $g = 5-10 \mu m$ when about $I_p = 1A$, $r_p = 2 \mu s$), leading to such abnormal conditions as short-circuits and electric discharge concentration.

$T_d = 0.22$ sec and $T_u = 0.53$ sec with the processing machine and processing liquid (Diamond EDF) used in the test (Note: In many cases T_u can be made longer if a processing liquid with a lower viscosity is used).

Then, a test was conducted to determine to what extent T_D could be extended if the ultrasonic vibration were added. Figure 2 shows the results of this test. In this case a very fine ultrasonic vibration with an amplitude of $\pm 1 \mu\text{m}$ (maximum amplitude $2 \mu\text{m}$) was adopted (Note: Since this is the amplitude under no load, the amplitude could become somewhat smaller if fluid resistance is present in the processing liquid).

As shown in Figure 2, T_D gradually increases when a small ultrasonic vibration, whose amplitude is $\pm 1 \mu\text{m}$, is added, compared to the normal electric discharge without the ultrasonic vibration, and the figure shows that stabilized processing is conducted in the end, even if $T_U = 0$, without lifting the electrode. In comparing the processing depth at this time, the processing speed of $T_U = 0$, to which the ultrasonic vibration is added, becomes about 2.2 times that of the normal electric discharge. From this it is clear that the addition of ultrasonic vibration is effective. In short, it has become possible to eliminate most of T_U , the nonprocessing time, using an amplitude ultrasonic vibration of $\pm 1 \mu\text{m}$.

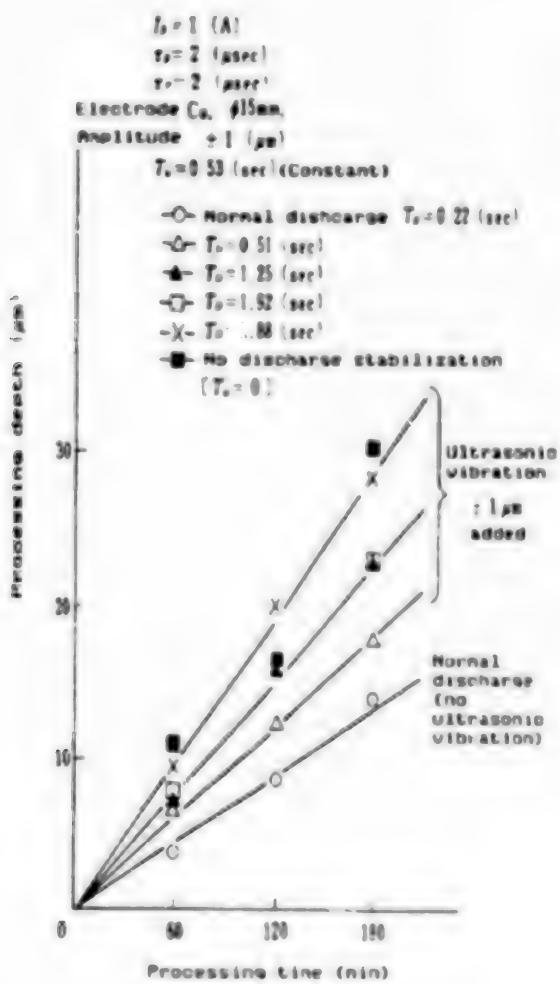


Figure 2. Relationship Between Processing Time and Processing Depth

Further, since the distance between electrodes is 5-10 μm when the amplitude is 1 μm , as shown in Figure 2, no short circuit is caused by the ultrasonic vibration.

Then, an interesting point will arise if the processing speed with the $\pm 1 \mu\text{m}$ ultrasonic vibration amplitude is the limit, or if it is increased if the amplitude is made greater, and if contacts or short circuits occur between the electrodes and the workpiece if the amplitude is great.

(2) Size of amplitude of ultrasonic vibration and processing efficiency

When extending the amplitude of ultrasonic vibration, the possibility exists that a short circuit will occur when the electrode approaches the workpiece due to the very short distance between electrodes, as mentioned above.

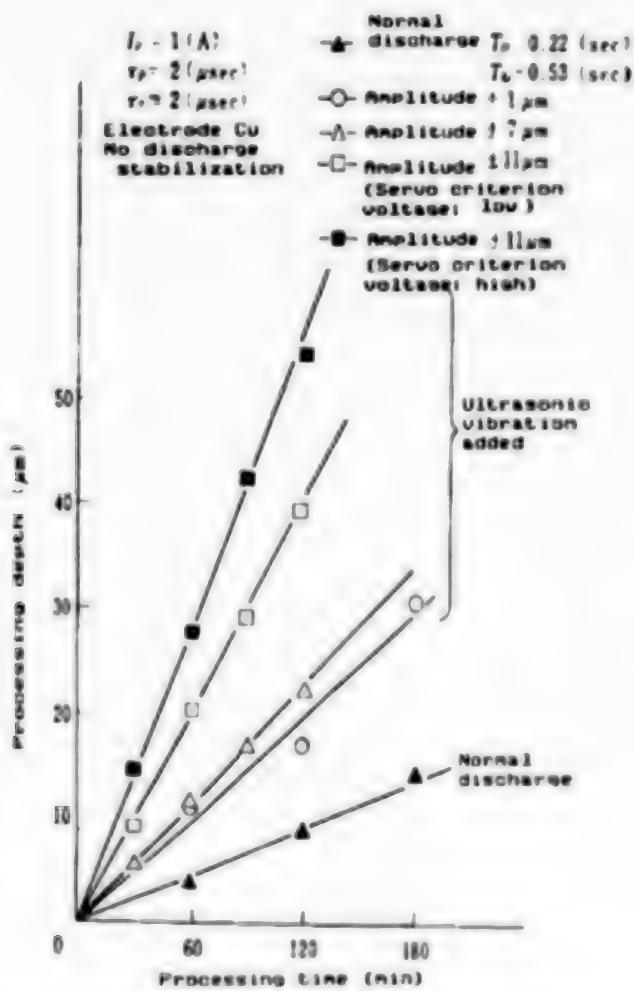


Figure 3. Relationship Between Processing Time and Processing Depth

Therefore, tests involving the two servo criterion voltage values were conducted; one was when the servo voltage between electrodes was lower than normal, and the other was when it was higher than normal. This means that the distance between electrodes becomes narrower when the value is low, and wider when the value is high.

Figure 3 shows the relationship between the processing time and the processing depth when the amplitude of ultrasonic vibration (the set amplitude at the no-load condition in the air assigned to the electrode is used as a parameter. The processing efficiency is extremely improved in the case of the servo voltage whose distance between electrodes becomes wide at the $\pm 11 \mu\text{m}$ set amplitude, and it is six to seven times that of the normal electric discharge and a little over three times that of a set amplitude of $\pm 1 \mu\text{m}$.

It is believed the reason for such improvement in the processing efficiency is that the scavenging effect became great through the ultrasonic vibration accompanied by the increase in amplitude. It was also determined that the actual amplitude during the processing was smaller than the nonload set amplitude (e.g., it was about 50 percent that of the amplitude during the processing of $\pm 7 \mu\text{m}$).

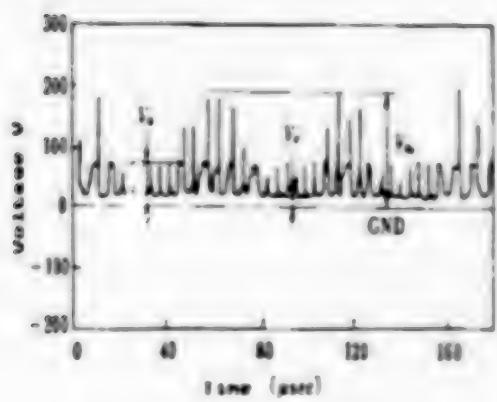
3.1 Height of Servo Voltage and Phenomena Between Electrodes

A simultaneous recording of the voltage and current between electrodes using the two sets of transient memory was attempted for the case of a high servo voltage (wide distance between electrodes) and for a low voltage when the amplitude was $\pm 11 \mu\text{m}$ with no load.

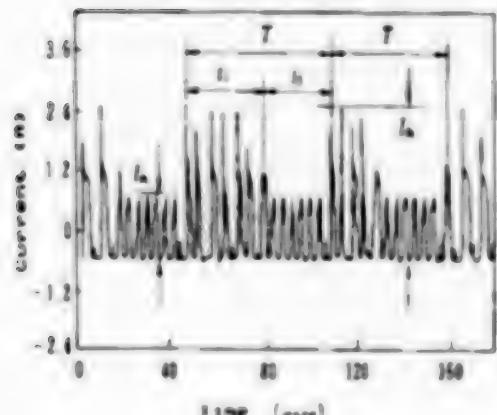
These are shown in Figures 4 and 5. Figure 4 shows a case in which the servo criterion voltage is high and the distance between electrodes is wide, and Figure 5 shows a case in which the criterion voltage is low.

In Figure 4, V_0 is no-load impressed voltage, V_s is discharge voltage, and T is the ultrasonic vibration cycle (about 20 kHz). The condition in the t_1 section makes it difficult to discharge since the electrode is away from the workpiece, however, on the contrary, in the t_2 section it is easy to discharge since the electrode approaches the workpiece. When the electrode is away from the workpiece, it cannot discharge right away even if the bath no-load impressed voltage rises to 8 V. After a short delay, discharge occurred when the high voltage impression made a forcible discharge. On the other hand, it can be understood that the discharge occurs as soon as the no-load impressed voltage reaches 8 V in the t_2 section since the electrode is close to the workpiece. V_s is the arc voltage when a current is flowing between the electrodes, that is about 20-25 V. This set condition can be termed very efficient since the discharge is conducted continuously (Figure 6(a)).

Figure 5 shows the waveforms when the criterion servo voltage between electrodes is low (Figure 6(b)). Under these conditions the electrode contacts the workpiece (hammering also occurs) since the distance between

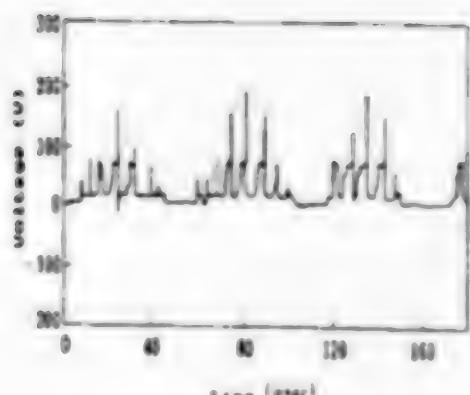


(a) Voltage waveform

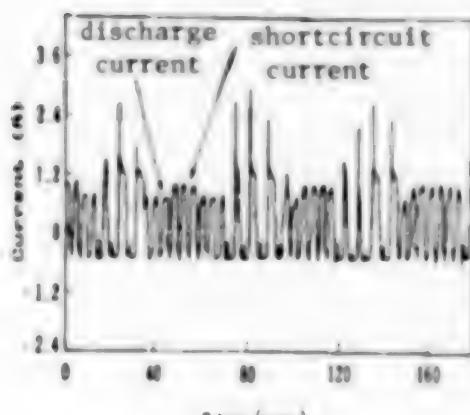


(b) Current waveform

Figure 4. Voltage Waveform and Current Waveform (Servo criterion voltage: High)



(a) Voltage waveform



(b) Current waveform

Figure 5. Voltage Waveform and Current Waveform (Servo criterion voltage: low)

electrodes becomes very narrow. This is explained by the fact that the voltage/current waveforms show a short circuit.

In the case of Figure 5, the main shaft indicates an irregular vertical motion because the short circuit detection circuit of the discharge processing machine also works.

3.2 Roughness of Finished Surface

Figure 6 shows the difference in surface profiles following processing.

In the case of Figure 4, where there is little contact between electrodes, not only can the high processing speed shown in Figure 3, but also an R_{max} of $0.8 \mu\text{m}$ for finished surface roughness can be obtained, which is less than half of the R_{max} of $1.9 \mu\text{m}$ found for the case of many electrode contacts, as shown in Figure 5.

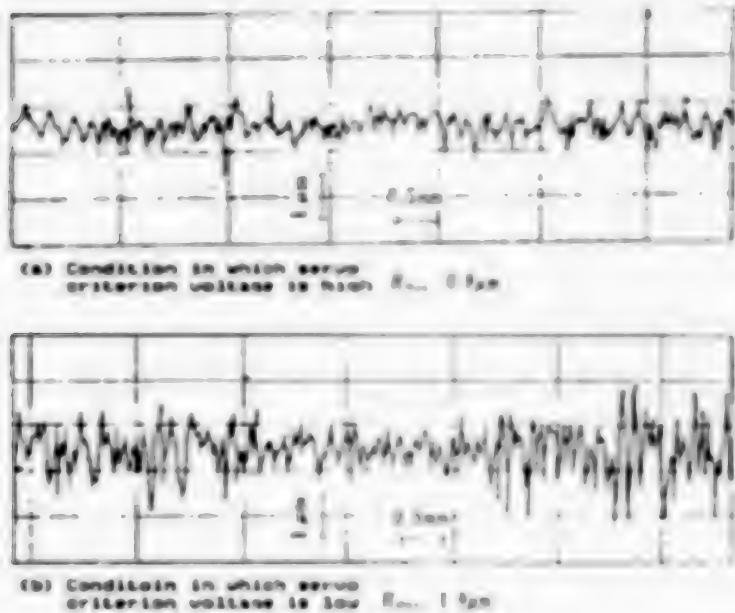


Figure 6. Servo Voltage and Surface Profile (Processing time: 60 min)

Therefore, it will become necessary to raise the criterion bath voltage to such that the electrode main shaft will not make an irregular motion and to widen the distance between electrodes in order to adjust the processing conditions.

3.3 Roughness Prior to Finish Discharge Processing and Finish Processing Speed

In conducting finish processing by discharge processing, the finish processing must start from the previous roughness.

Then, the asymptotic speed to the target roughness with and without the ultrasonic vibration will be compared for cases in which the roughness prior to processing is about 17 and 10 R_{\max} . Figure 7 shows the progress of the change of the finishing surface roughness and the processing time. The electrode base becomes a little rough through processing since it is not under low consumption conditions. Therefore, it does not become about $1 \mu\text{m } R_{\max}$, if even the roughness is saturated, but it can be observed that it proceeds to the target value at a very high speed with the ultrasonic vibration.

4. Conclusion

As a result of the discharge finish processing test giving ultrasonic vibration to the electrode for discharge processing, the following has been determined.

- 1) The processing efficiency will be improved by the scavenging effect of ultrasonic vibration, and it will be further improved since the electrode descending time t_d during the discharge stabilizing action can be extended. It is also effective with an amplitude of $11 \mu\text{m}$.

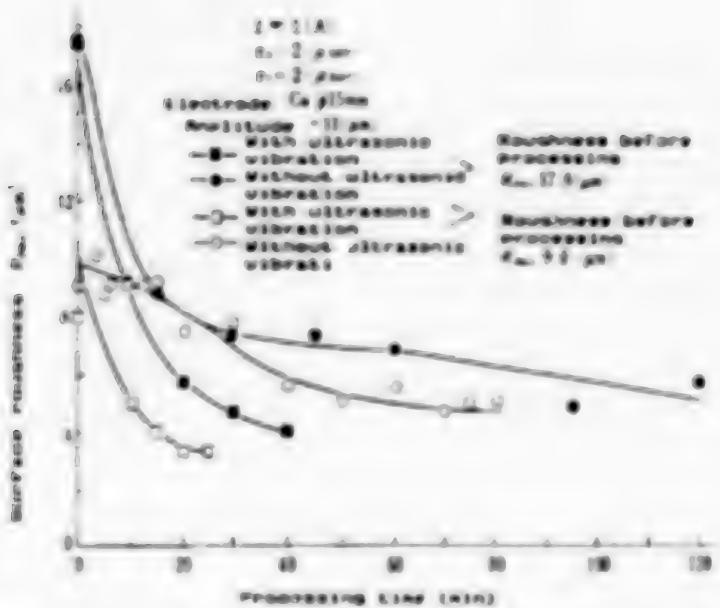


Figure 7. Relationship Between Processing Time and Surface Roughness

- 2) The roughness of the finished surface will be slightly improved compared with that of the ordinary mirror finish processing when the bath servo voltage and ultrasonic vibration amplitude that do not produce ultrasonic hammering are selected.
- 3) It is preferable to adequately control the distance between electrodes and the ultrasonic vibration amplitude utilizing the voltage-current waveforms between electrodes.

The problem in this processing method involves how to vibrate the electrode of an optional shape, and we are eagerly working to establish this method.

20155/9365

Laser Beam Heat Method Reported

43064023h Tokyo KIKAI TO KOGU in Japanese Jan 88 pp 66-70

[Article by Hachiro Tsuchiya and Hidekazu Goto, Kyoto University of Industrial Arts and Textile Fibers: "Ceramics Processing Utilizing Laser Induced Thermochemical Reaction"]

[Text] 1. Introduction

The laser processing method is one of the processing methods used to remove solid material, which is currently being applied to various materials. However, since the past laser processing method conducted removal processing by local heating, fusion, and evaporation of the material by making the material absorb laser beams of high energy density, problems existed due to the higher energy laser being required when the absorptivity of the material itself was low or when the decomposition and evaporation temperatures were high and, therefore, the processing efficiency became low. In particular, since fine ceramics are generally fragile materials with high fusion points, various problems are involved, such as the occurrence of cracks by thermal shock, the decline in processing precision by the formation of melted and re-solidified layers, and the destruction of the materials' properties by the heat. In addition to the processing efficiency problems mentioned above. One of the methods possibly capable of solving such problems is the processing method utilizing a laser-induced thermochemical reaction.

It is believed that methods exist in which the optical chemical and thermochemical reactions are used to conduct the removal processing of solid material by inducing a chemical reaction utilizing the laser energy. The former induces the chemical reaction by exciting the gas molecule on the surface of the material and the electron in the material by using the laser's optical energy directly. Generally, since a laser with a shorter wavelength than that of the ultraviolet region is used, and the manufacturing process progresses at a low temperature, its application to the fine processing of semiconductor materials is being tried, for which the destruction of the materials' properties has been an especially notable problem.

On the other hand, the latter induces the thermochemical between material's surface and the gas molecule or the etchant by heating the material's surface, making the material absorb the optical energy of the laser. The

laser beam in the visible to infrared region is considered appropriate. Its weak point is that the material reaches a high temperature, but it also has some strong points, and the etching of semiconductor material is being conducted.

The authors and others are conducting research involving the decomposition process of the molecule at the solid surface and the removal mechanism of the surface layer for the processing method using a thermochemical, and conducting experiments involving the processing characteristics of semiconductor materials and ceramics for future application. Reported here are the results of the application of the thermochemical to the CO₂ laser processing of ceramics, and the possibilities presented by this processing method are examined.

2. Basic Process of Laser Induced Thermochemical Reaction Processing

Figure 1 shows the manufacturing process of laser-induced thermochemical processing using the reaction gas divided into three stages. A local high-temperature area is formed by the laser irradiation on the material in the reaction gas (Figure 1(1)), the formation of the reactant and the decomposition of the surface layer are conducted by the thermochemical induced there (Figure 1(2)), and, if the volatility of this reactant or the surface layer is high, the removal processing progresses efficiently (Figure 1(3)).

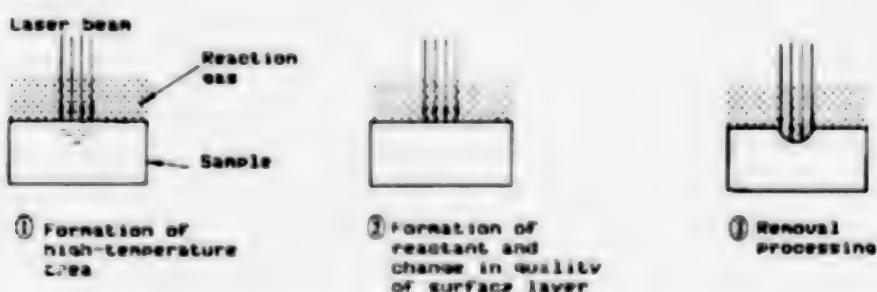


Figure 1. Manufacturing Process of Laser-Induced Thermochemical Reaction Processing

On the other hand, although the manufacturing process is a little different, there is a method that uses the reaction solution for the reaction gas. For example, it has been determined that when the KOH water solution is used excellent processing can be conducted, such as laser processing with lower power than the ordinary laser processing, and melted and re-solidified layers or cracks will not be produced on the processing surface. However, this method is only effective for several kinds of ceramic materials, and no effective methods for metallic oxide ceramics, such as ZrO₂ and Al₂O₃, has been reported. Then, the authors and others tested the CO₂ laser processing in the CF₄ gas atmosphere as an effective method for metallic oxide ceramics as well, and examined its results. The CF₄ gas molecule is used as the etching gas in the plasma etching of semiconductor materials because it can etch Si, etc., by exciting and decomposing it using serial discharge, etc.

Following is an outline of the basic processing course during the thermochemical processing of ceramics using this DF_4 gas.

Figure 2 shows the relationship between the temperature of the center of the laser-irradiated section and the laser power when the CO_2 laser is irradiated on ZrO_2 , Al_2O_3 , and Si_3N_4 . This was calculated on an infinite plate, 2 mm thick, making the laser spot diameter 180 μm , and the temperature dependency of the heat conductivity was taken into consideration. Each sample shows the temperature rise to the fusion point. This indicates that these three kinds of ceramics can possibly be processed by fusion processing with a laser whose maximum output is about 20 W, and it can be determined that the processability of these are in the order of ZrO_2 , Al_2O_3 , and Si_3N_4 .

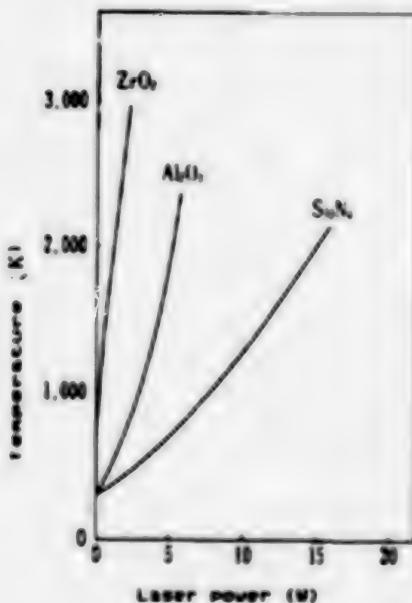


Figure 2. Relationship Between Laser Power and Temperature at Center of Laser-Irradiated Section

As the next process, the reaction gas molecule collides with the region heated by the laser irradiation, inducing a thermochemical. For this purpose, it is necessary that the decomposition reaction of the CF_4 gas molecule occur first. Energy of 4-5 eV is required to decompose the CF_4 gas molecule existing alone, but it has been found that the decomposition reaction of the CF_4 gas molecule occurs on the surface of an Si single crystal when the surface is heated to about 900°C, and Si is etched. The melting temperature of Si is about 1,400°C, showing that processing progresses at a temperature under the fusion point when the thermochemical is utilized.

The energy that the CF_4 gas molecule can receive from the Si surface at this time averages about 0.1 eV, and it will be decomposed with energy somewhat less than that when the CF_4 gas molecule exists independently.

The authors and others believe that this is due to a new anti-bonding orbital which is produced at the low energy position in the CF_4 molecule by the correlation between the CF_4 molecule and the Si monocrystal surface, and the electron enters into this orbit from the Si monocrystal side.

It is believed that such a chemical reaction, in which the solid surface is made a catalyst, involves several interesting matters, but this will not be discussed at this time since it would digress from the subject.

Finally, there is a process in which the reactant or the surface layer formed by the thermochemical in the CF_4 gas evaporates. To investigate the volatility of the surface reaction layer of ceramics, the CF_4 gas molecule was decomposed beforehand by aerial discharge and CO_2 laser processing was conducted providing the ceramics surface with the decomposed molecule. Figure 3 shows the relationship between the laser power and the processed hole's depth for Al_2O_3 , with the laser spot diameter being 360 μm . The results of processing in air plasma are also shown. It is seen that the processing is conducted using about half the laser power required for processing in air, and a highly volatile surface reaction layer is formed on the sample by the excited and decomposed CF_4 gas molecule. Similar results have also been obtained for ZrO_2 .

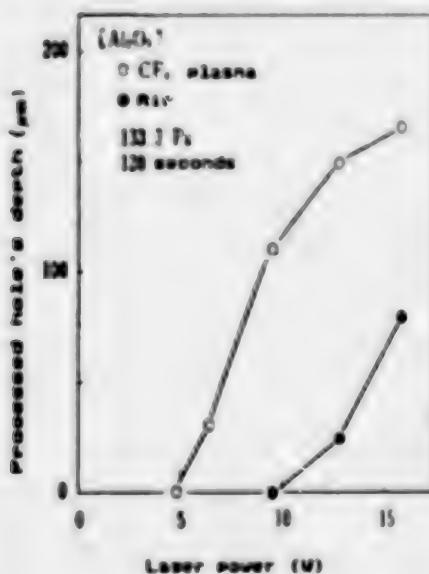


Figure 3. Relationship Between Laser Power and Processed Hole's Depth in CF_4 Plasma

It is believed that the processing characteristics of this processing method will be chosen by combining individual characteristics of the basic process, as mentioned above, and the establishment of the theoretical formula for the processing characteristics and the experimental verification will be subjects for future discussion. Following is a report on the processing characteristics observed when the laser processing of ceramics was actually conducted using CF_4 gas, and the possibilities for this processing method will be examined.

3. Laser Processing of Ceramics in CF₄ Gas

Figure 4 shows an outline of the processing device. The oscillation wavelength of the CO₂ laser is 10.6 μm , and the maximum output is 30 W. The laser is led into the same container through a ZnSe lens with a 60 mm focal distance, and is condensed on the sample's surface with a spot diameter of about 180 μm . The CF₄ gas flows into the sample container from the upper part of the sample at a flux of about 40 cm³/min. The processing in the air was also conducted with the same air flow flux for comparison.

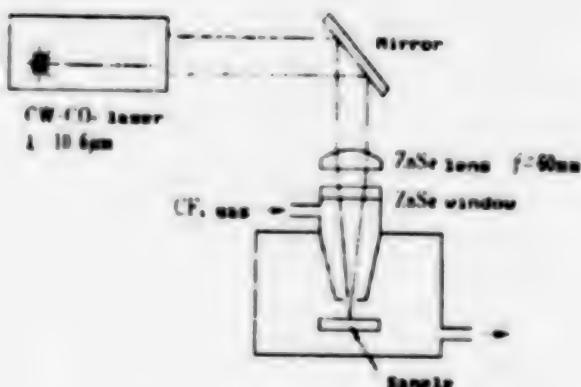


Figure 4. Sketch of Laser Processing Device

The samples consist of ZrO₂, Al₂O₃, and Si₃N₄ ceramics, and are squares 5 $\mu\text{m} \times 5 \mu\text{m}$ and 2 mm thick. The surface roughness is 5 μm , 2 μm , and 2 μm , respectively. Y₂O₃, SiO₂, and Al₂O₃ are contained, respectively, as impurities.

Figures 5-7 show the relationship between the laser power and the processed hole's depth for each of the three ceramics. The laser irradiation time is 10 seconds, and the results of processing in the air are also shown. The depth of each sample processed in the CF₄ gas is increased several times over that processed in the air, and it can be seen that the processing efficiency has been improved by the CF₄ gas. This suggests that the decomposition reaction of the CF₄ gas and the formation of the highly volatile surface reaction layer actually occur on the laser-irradiated surface. However, even in the CF₄ gas, the required laser power for starting processing is only several percent less than that required for processing in air, and it can be seen that the thermochemical is not induced unless the sample surface temperature is raised at least close to the fusion point. Figure 8 shows the relationship between the laser power and the processed hole's diameter, and the diameter in the CF₄ gas is bigger than that in the air. It can also be determined from this that the thermochemical occurs at a temperature a little lower than the fusion point.

Photo 1 is a processed hole of ZrO₂ in the CF₄ gas, and Photo 2 is a hole in the air. Swells and cracks are observed around the hole in the air, but

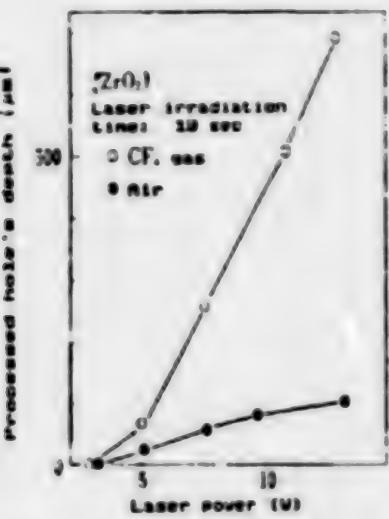


Figure 5. Relationship Between Laser Power and Processed Hole's Depth in ZrO_2

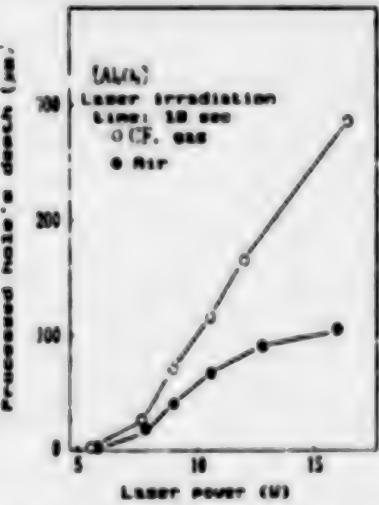


Figure 6. Relationship Between Laser Power and Processed Hole's Depth in Al_2O_3

they are not seen in the CF_4 gas, indicating that excellent shape processing can be conducted in the CF_4 gas. Photo 3 shows the processed surface in the CF_4 gas, and Photo 4 shows the processed surface in the air. The processed surface in the air is a melted and re-solidified s with cracks, and the processed surface in the CF_4 gas is a surface where sintered molecules are exposed with no melted and re-solidified layers. The same results were obtained for Al_2O_3 and Si_3N_4 .

As stated above, a highly volatile surface reaction layer could be formed by the thermochemical between the CF_4 gas and the ceramics surface, and it has become clear it is possible to conduct processing with higher efficiency and precision than those of laser processing conducted in air. Since the low-output CO_2 laser was used in this test, only data for laser power less than 20 W could be obtained. It is believed that if similar

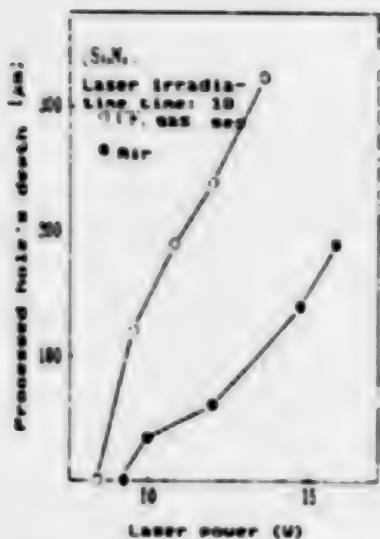


Figure 7. Relationship Between Laser Power and Processed Hole's Depth in Si_3N_4

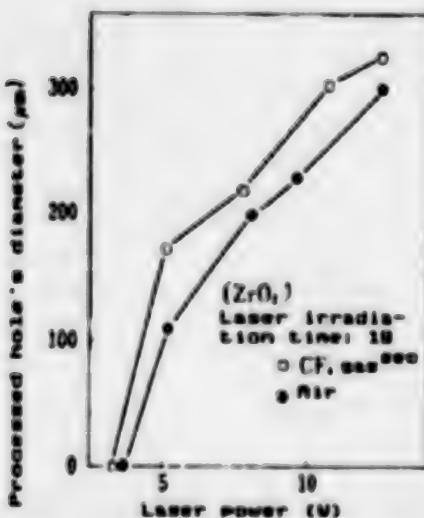


Figure 8. Relationship Between Laser Power and Processed Hole's Depth in ZrO_2

superior processing characteristics are obtained when a higher power laser is used, more practical tests, such as cutting and the three-dimensional processing of complicated shapes of ceramics materials, can be conducted. It is also believed that it is necessary to conduct measurements of the change in the properties of the processed surface and the mechanical strength of the materials.



Photo 1. ZrO₂ Hole Processed in
CF₄ Gas

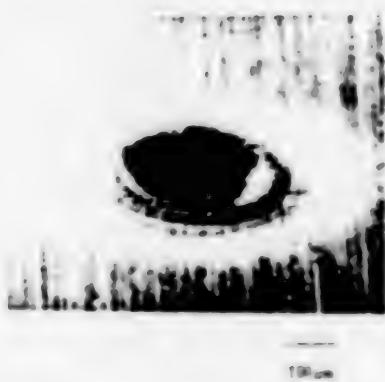


Photo 2. ZrO₂ Hole Processed in
Air



Photo 3. ZrO₂ Surface Processed
in CF₄ Gas



Photo 4. ZrO₂ Surface Processed
in Air

4. Conclusion

An outline of research involving the processing method utilizing the laser-induced thermochemical has been presented, with the CO₂ laser processing of ceramics in CF₄ gas used as a practical processing example, and its processing characteristics and related subjects will be discussed in the future. It has become clear that it will be possible to conduct laser processing of ceramics with high efficiency and high precision by utilizing the thermochemical, but it is not believed that the present method is the best one and it is not clear that it can be applied to commercial processing. It is thought that the processing characteristics of this method will be greatly changed by the combination of the atmospheric gas and the material, and it is important to conduct tests on various combinations. However, it is believed that the improvement and development will become possible by theoretically confirming the basic process of the processing, especially of the thermochemical process between the solid surface and the atmospheric gas molecule. Actually, it is believed that the thermochemical process on the solid surface is quite complicated. For example, it has been confirmed that when thermochemical processing the Si monocrystal in the CF₄ gas, the processing speed would change by at least

10 times through changing the gas pressure and the mixing O₂ gas density. However, conversely speaking, it is believed that the fact that this method is complicated, with many unexplained points and room for research, conceals the possibility of its being applied to various fields, and also, in this sense, the quantitative confirmation of its basic process is an important problem to be solved in the future.

20155/9365

Microdrilling Using Electron Beams Reported

43064023i Tokyo KIKAI TO KOGU in Japanese Jan 88 pp 71-78

[Article by Megumi Omine, Production Technology Laboratory, Mitsubishi Electric Corp.: "Microdrilling Using Electron Beams"]

[Text] 1. Introduction

In the mid-1950s electron beams came to be used for heat-applied working. In the early days, they were used, for example, to weld zircaloy in manufacturing containers for nuclear fuel rods or to melt active metals by utilizing their ability to heat materials in a reduced-pressure environment. It was later found that an electron beam whose power density had been raised to about 10^6 W/cm² could achieve deep penetration, enabling efficient low-strain welding without causing much of a thermal effect on the workpiece. Subsequently, various fundamental electron beam working techniques were established. Among these techniques are those that increase the output power of electron beams, lengthen the lives of electron guns, and are used for localized beam formation or continuous beam formation in a vacuum, and for computerized working-parameter control. Since then, electron beam applications have been increasing in such fields as automobiles, space and aeronautics, and heavy machinery. However, the applications have been almost limited to welding.

Recently, as diversified possibilities for electron beams have arisen one after the other, hopes are being placed on the feasibility of electron beam microdrilling while fabricating electronic devices or precision mechanical parts. While manufacturing such devices or parts, it will be necessary to drill many densely arranged microholes, ranging in diameter from several tens of μm to several hundred μm , at high speed with an accuracy of several μm to several tens of μm . To enable such microdrilling by means of an electron beam, it is necessary to make maximum use of the features of electron beams, such as 1) electron beams can be converted into microspots using convergent lenses to conduct microfine processing; 2) electron beams can be controlled using deflection coils to scan arbitrarily specified areas on the workpiece surface at high speed, enabling flexible working on selected areas; and 3) since electron beams can deliver a high density of energy, they can be used to work both hard and soft materials.

Figure 1 shows the technological trends toward electron beam-applied working. As it shows, in the field of welding or heat treatment the trend is toward reducing electron beam diameters, which presently range from several hundred μm to several thousand μm , down to several tens of μm , enabling finer electron beam working. In the field of drilling, it is aimed at raising the power density of pulsed electron beams from the order of 10^7 W/cm^2 to 10^8 W/cm^2 , thereby enhancing the accuracy of the electron beam working. Furthermore, in the field of electron microscopes or with regard to ultrafine electron beams whose diameters are on the order of several hundred nanometers and which are used to plot masks for VLSI fabrication, the technical trend is toward enhancing the beam output and the scanning speed and accuracy in order to permit larger-area exposures. In addition, progress is also being made on techniques to control electron beams, with regard to both time and space, at high speed, to simultaneously control many parameters involving electron beam working, and to detect weld lines or beam focal points through reflected-beam detection. Therefore, in the field of electron beam working technologies, a fresh development toward realization of faster and finer processes has started to take place.

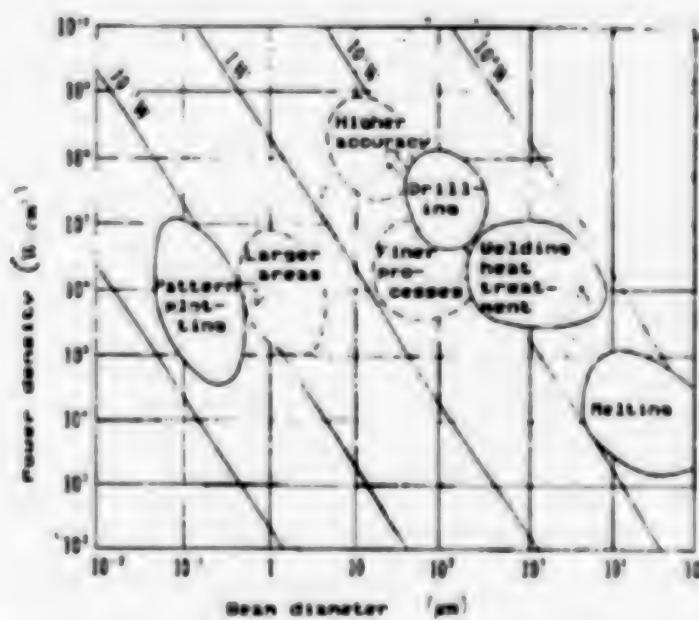


Figure 1. Trends of Electron-Beam Working Technologies

This paper describes the concept of microdrilling through the pulsed electron beam technique that the author has developed jointly with other researchers, an outline of the development of the technique, application examples, and relevant targets to be achieved in the future. We have developed the technique based on the recognition that the inherent features of electron beam working cannot really be utilized unless fine beam-energy control is made possible.

2. Concept of Pulsed Electron Beam Working

2.1 Principle of Pulsed Electron Beam Working

The size of the material area to be worked by an electron beam can be controlled just by controlling the time and space aspects of the beam energy. The beam-working depth is affected the most by the beam power density. To control the beam-working depth, it is also necessary to properly control the working speed and time. The working time is controlled by setting the proper working speed. The width of the beam-worked area is naturally dependent on the beam diameter. In addition, it has been found from the results of measuring beam-energy distributions, observing the interactions between electron beams and the materials worked on, and analyzing the observed interactions in light of the theory of heat conduction that the width of the beam-worked area is also closely associated with the width of the heat-affected zone and the amount of heat conducted from the beam-working spot. The heat-affected zone is formed by the effect of the low-energy portion of the electron beam. To begin with, in electron beam working, it is ideal to realize a minimum required width of beam working while maintaining an adequate depth of beam working. In order to realize such ideal beam working, it is effective to achieve a steep distribution of beam energy density and control the time of the beam energy.

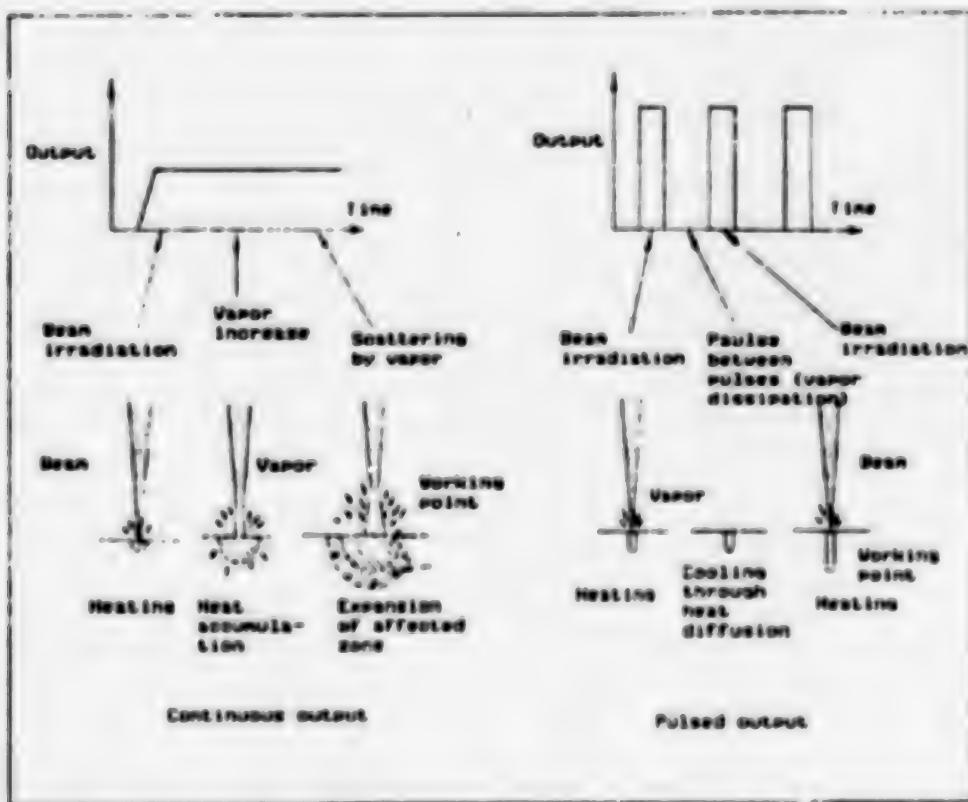


Figure 2. Principle of Pulsed Electron Beam Working

As shown in Figure 2, in ordinary heat-applied working conducted using a continuous electron beam, the working conditions cannot be adequately controlled and the heat generated in the working spot affects a large peripheral area. In such beam working, the continuous beam energy overheats the working spot and allows heat accumulation in the peripheral area. Beam irradiation also causes, after a certain time lag, material evaporation, and the vapor generated by evaporation scatters the electron beam. As a result, the beam energy density is reduced and the heat-affected zone is expanded.

If the electron beam output is pulse-controlled while the pulse peak output needed to achieve a required working depth is secured, the time in which the heat is generated at the working spot and then spread to the peripheral area in the unit is reduced. Furthermore, the heat spread to the peripheral area is quickly dissipated in the workpiece during the intervals between pulses, preventing heat accumulation in the peripheral area. Therefore, a heat-affected zone is scarcely formed. In pulsed electron beam working, extremely short electron beam pulses are used. Therefore, each beam pulse ends before the vapor generated as a result of its emission rises and the next pulse is emitted after the vapor is dissipated during the pause. In this way, the pulse beam is prevented from being scattered by the vapor.

As shown in Figure 3, in a continuous electron beam, energy density is high in the beam center and low in the outer portion of the beam. While such a beam continues to be emitted onto the workpiece surface, its outer portion, with a low energy density, also starts showing its effect, resulting in expanding the heat-affected zone. When such a continuous beam is transformed into pulses, the low energy portion of the beam is virtually eliminated and, as a result, a beam with a high energy density can be obtained.

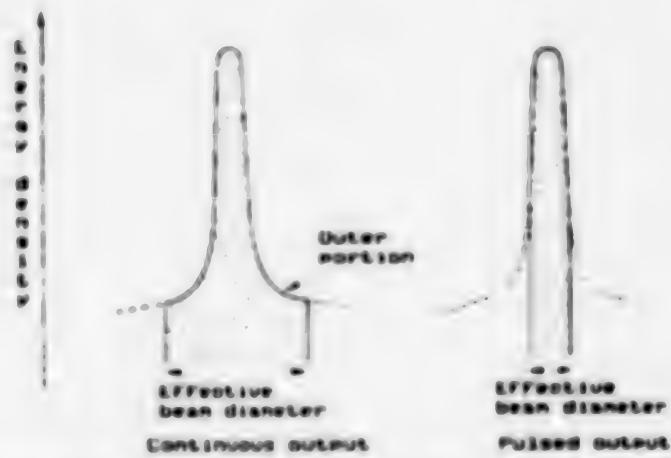


Figure 3. Effective Energy Density Profiles of Electron Beams

2.2 Features of Pulsed Electron-Beam Working

The effects of using pulsed electron beams on the manufacturing techniques include the following:

(1) High-precision peripheral area is enabled

Pulsing an electron beam results in a finer effective beam diameter, enabling working on a finer area. Therefore, pulsed electron beams can be used to work fine parts or microdevices, which used to be inappropriate as objects for heat-applied working, thereby achieving higher productivity.

(2) Working less affected by heat generation

When a pulsed electron beam is used, heat generation at the worksite can be held to the minimum required level, reducing the time during which the area around the worksite is subjected to a high temperature. As a result, it becomes possible to retain the intrinsic properties of the material being worked.

(3) Working is based on new concept

Electron-beam working is governed by phenomena closely related to the conditions of beam irradiation and is subjected to restrictions attributable to such phenomena. Adoption of pulsed electron beams makes it possible to introduce a new concept of electron beam working, free from the mechanism of conventional electron beam working with a continuous output format. The dot quenching method is an example of a new technique based on the new concept. In the new method, the beam spot location and the number of beam pulses emitted are also used as control factors, in addition to such conventional factors as the beam power density and the duration of beam irradiation.

3. Outline of Development of Pulsed Electron-Beam Working Technique

3.1 Development Aims

Along with the dissemination of highly advanced technologies in the industrial world, many materials, such as composite materials and so-called "new materials" to which the conventional material working methods cannot properly be applied, have been introduced. As a result, it has become necessary to develop new high-performance methods of material working based on new concepts. Particularly, work objects that require the drilling of many microholes have been on the increase. For example, in the field of PC boards where increasingly high-density products are in demand, glass-cloth substrates require 500 to 1,000 holes, with diameters on the order of 100 μm , to be drilled in every dm^2 [as published] of area. In the field of aircraft, in developing a laminar flow control-type wing, it is necessary to drill numerous holes measuring 70 μm in diameter and on the surface of a wing made of a titanium alloy with as small a spacing as 700 μm .

The conventional drills used for microdrilling pose many problems: They break easily, their achievable drilling speed is low, and they cannot be used to drill holes with very small diameters. Therefore, the introduction of a technique for contactless drilling which causes no tools to be worn has long been awaited. The pulsed electron beam method is among the measures that can be used for such drilling. It enables microholes with diameters of 100 μm or less to be drilled with ease at a rate of 5,000 holes per second, that is, at least several hundred times faster than is possible using the conventional method. The introduction of this method may result in innovating the beam-applied manufacturing process technique.

3.2 Contents of Development

(1) Pulsed electron beam working system

Figure 4 shows a system block diagram of the new pulsed electron beam working system. The system is broadly divided into a high-voltage generating section, an electron gun system, a work chamber, and a computer section to control operations of the other sections. Their functions and major specifications are described in the following:

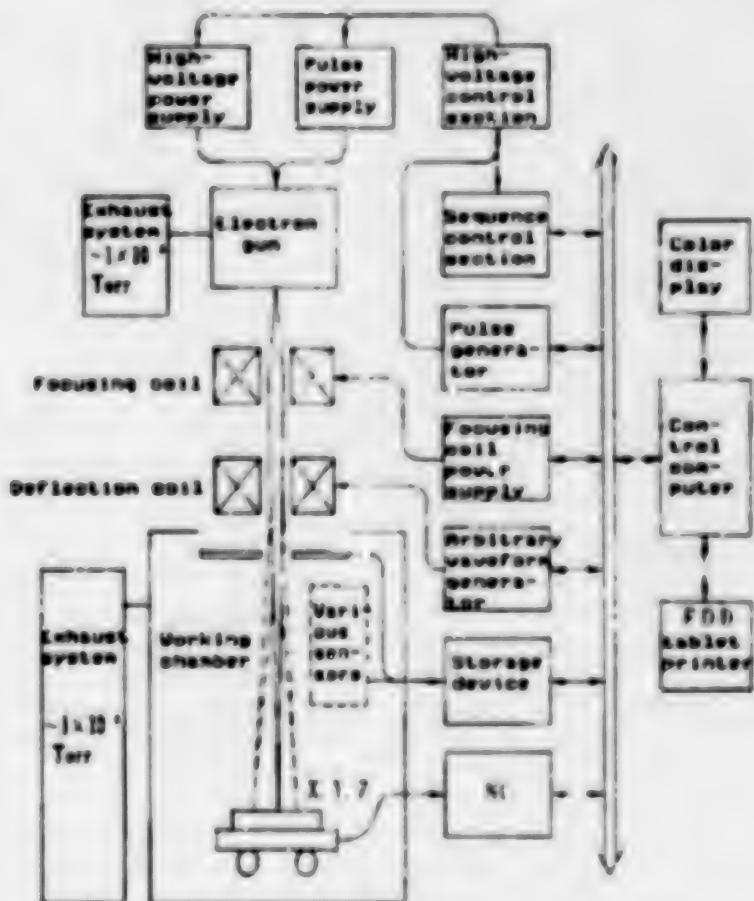


Figure 4. System Block Diagram of Pulsed Electron Beam Working System

a. High-voltage generating section

This section consists of a high-voltage power supply, a pulse power supply, and a high-voltage control system. It controls beam output (beam current and acceleration voltage) and beam pulsing. Its rated voltage is 180 kV maximum; pulse peak current is 100 mA; and pulse frequency is 100 to 50,000 Hz.

b. Electron gun system

This system consists of a cathode, an anode and a Wehnelt cylinder, needed for electron beam generation, and a coil needed for electron beam focusing or deflection. The cathode used in this system is a unique rod-type hot cathode.

c. Work chamber

This chamber is designed to be capable of maintaining a vacuum as high as 10^{-4} torr. For ordinary working, it is kept at a pressure of 10^{-3} to 10^{-4} torr. In this chamber, an NC table (with a positioning accuracy of $\pm 5 \mu\text{m}$), which can move workpieces along its X, Y, or Z axis, and various sensors for monitoring the conditions of working are installed.

d. Computer control section

This section contains an HP model 9920 which incorporates a 16-bit CPU. It has been adopted based on the concept that a computer used to control the operation of the entire system requires high-speed processing capability. A 20-MHz pulse function generator used for pulse waveform control is also included in this section.

(2) Adoption of rectangular short pulses and suppression of electric fluctuations

Pulsed electron beam working requires the beam output to rise steeply. To meet this requirement, we adopted, as shown in Figure 5, a multistage FET (field effect transistor) circuit for high-speed switching. We interconnected the power supply and the electron beam gun directly in order to reduce the capacitance of their connection, thereby raising the response speed. As a result, we succeeded in generating beam pulses with a nearly rectangular waveform and that require only $1\text{-}2 \mu\text{s}$ before rising to a 10 mA level. To provide the grid voltage for beam current control, we used dropper circuits without installing any special power supply. Therefore, with only one power supply incorporated in the system, voltage fluctuation was held to 0.05 percent or lower.

In addition, due to the adoption of a transistor inverter, the beam current fluctuation is held within ± 0.01 percent. Therefore, a highly stable, pulsed electron beam has been made available.

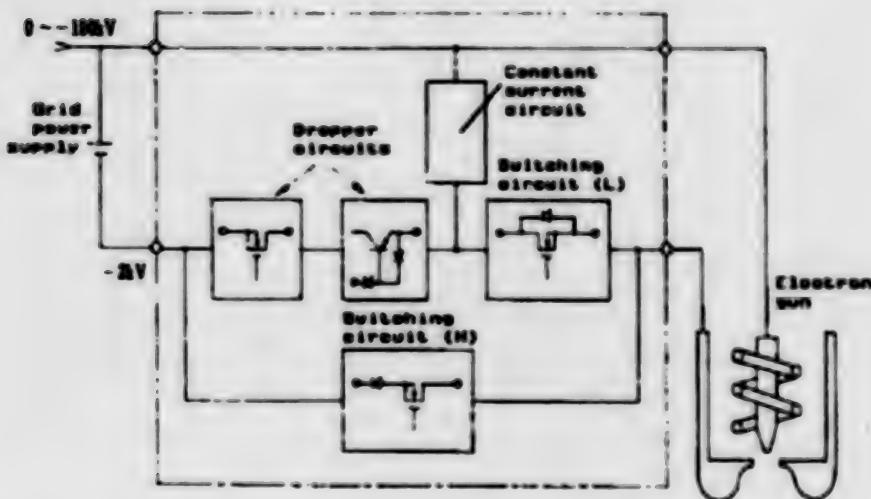


Figure 5. High-Speed Switching Circuit Incorporating FETs

(3) Enhanced electron beam luminance

In pulsed electron beam working, and particularly, in the case of drilling, factors such as the beam luminance and beam profile are directly reflected in the outcome. Therefore, in such working, it is very important to use a high quality electron beam. We developed an electron gun which can emit a high-luminance electron beam with minimal aberration. It contains optimally shaped electrodes which have been designed based on the results of electromagnetic field analysis through CAE [computer aided engineering].

In assessing the quality of a pulsed electron beam, it is important to be informed of the power density distribution in the beam. As a method of focal-point beam profile measurement, we adopted the sharp edge method. A block diagram of the measurement system is shown in Figure 6.

To measure the profile of a pulsed electron beam in this system, the beam is made to make a scanning motion at a constant speed and current changes occurring in the Faraday box when the beam is blocked by the "sharp edge" are observed. Specifically, it is assumed that, as shown in Figure 7, the power density in the electron beam changes, in stages, from concentric zone P_1 to P_2 , then to P_3 ; also, the beam current values measured are differentiated to calculate the amounts of energy injected into sectional elements S_1 through S_6 .

Figure 8 shows results of measuring the power density distribution on an electron beam while changing the magnitude of the current flowing through the focusing coil to adjust the beam focusing point relative to the measurement location, i.e., the sharp edge. As it shows, the beam core luminance at the focal point exceeded 10 MW/cm^2 and the measured beam profiles were very steep.

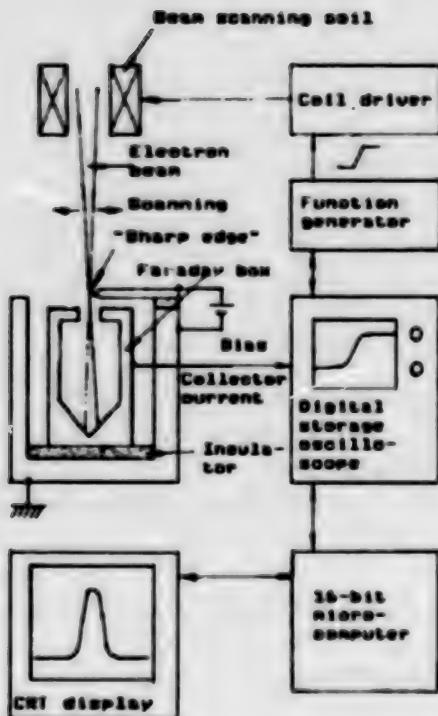


Figure 6. Beam Profile Measurement System



Figure 7. Principle of Beam Profile Measurement

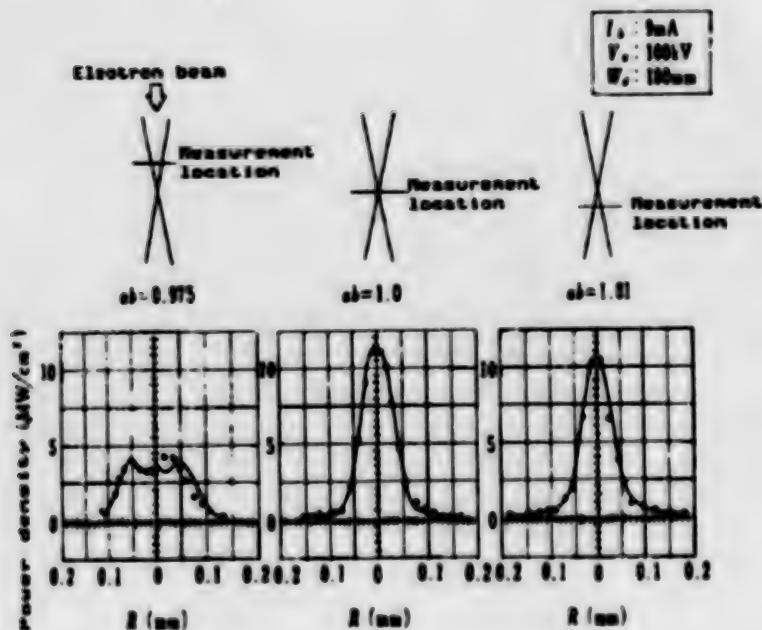


Figure 8. Beam Profile Measurement Examples

The peak power density is proportional to the beam current as is the acceleration voltage to the three-thirds [3/2] power.

4. Pulsed Electron-Beam Applications

4.1 High-Speed Microdrilling of PC Boards

Generally, PC boards are made of composite material (FRP) such as glass epoxy. Such PC boards used to be drilled mechanically, i.e., using drills. It is very difficult to mechanically drill through-holes measuring 0.2 mm or less in diameter. In fact, it used to take several tens of minutes to mechanically drill such small holes in a PC board.

Table 1. Thermal Properties of PC Board Constituents

	Thermal conductivity (cal/cm·deg·sec)	Specific heat (cal/g·deg)	Melting point (°C)
Copper	923×10^{-3}	0.919	1,083
E-glass	2.5×10^{-3}	0.197	840 (softening)
Epoxy resin	0.43×10^{-3}	0.25 (estimate)	180 (softening)

In such a situation, it is natural that expectations be placed on electron beam drilling. However, since the thermal properties of the materials

making up the PC boards, such as epoxy resin, glass, and copper, differ substantially as shown in Table 1, when holes are produced in a PC board using an electron beam, the inner surfaces of the holes become heavily rugged due to the formation of a heat-affected zone (carbonized zone). It is difficult to subsequently copper-plate these rugged hole surfaces. For this reason, beam drilling used to be impractical.

We have succeeded in reducing the magnitude of formation of such a heat-affected zone in electron working to a practically negligible level by improving the electron beam luminance, using short beam pulses instead of a continuous beam, and optimizing other work conditions. Now that the electronic circuits are integrated in increasingly high density and increasingly large quantities, the PC boards (e.g., double-sided PC boards and multilayer PC boards) for high-density circuit integration require a large number of microholes to be drilled in them during the fabrication process. The new technique we developed can be used to accomplish such microdrilling. Photo 1 shows through-holes drilled in a PC board using a pulsed electron beam.

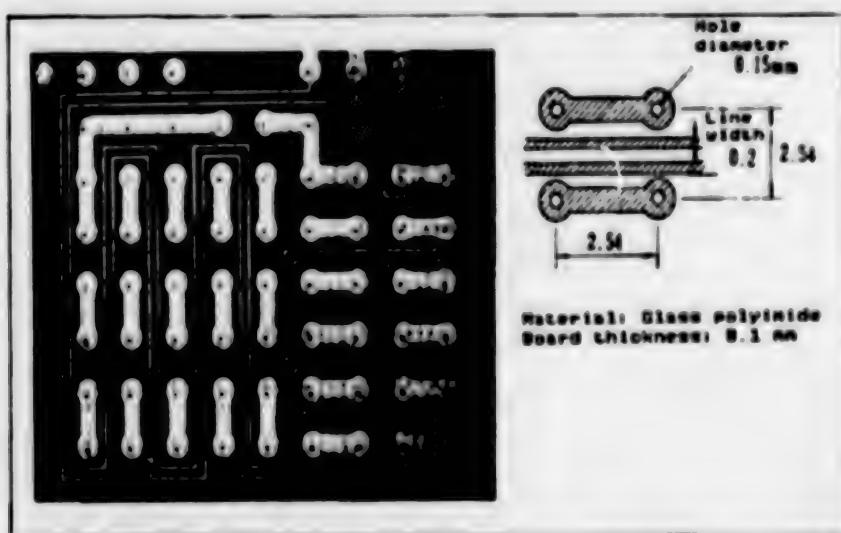


Photo 1. Through-Holes Drilled in PC Board Using Electron Beam

In Table 2, the performances of pulsed electron beam drilling and conventional mechanical drilling are compared. The comparison was made by assuming a drilling process in which 20,000 holes with a diameter of 0.3 mm are to be produced in a double-sided copper-plated multilayer PC board for inner-layer wiring (0.2-mm thick glass epoxy resin board with 0.07-mm thick copper coating) measuring 300 mm x 400 mm x 0.2 mm. If mechanical drilling is conducted by setting the drill speed to 6,000 rpm and the Z-axis feed to 1,000 mm/min, a hit rate of 1 to 1.5 hits/s will be achieved, while the time required for NC table feed is ignored. If, with these settings, two PC boards set together, one over the other, are drilled at the same time using a drilling machine in which four drills are set, eight holes can be drilled with every hit. In this way, it takes approximately 30 minutes to finish drilling a PC board (throughput).

Table 2. Comparison Between Mechanical Drilling and Pulsed Electron Beam Drilling of PC Boards

	Mechanical drill	Pulsed electron beam	Remarks
Working speed (Throughput)	30 holes/s (30 min/board)	5,000 holes/s* (2.5 min/board)	*Throughput by e-beam is 10 times higher or more
Hole diameter	#0.2 or larger	#0.1-1.0	
Life	Drill: Up to 1,000 hits (annual drill cost: ¥20 million)	Electrode: 100 million hits or more* (¥20,000/set)	*Virtually infinite
Work material	Ceramics, Kevlar, etc. Very stiff materials are inappropriate	Any material	
Setting change	Necessary for different diameters	Unnecessary	
CAD-compatibility	Connectable via NC	Directly connectable	

(Compared for PC board size 300 x 400 x 0.2 mm, hole diameter 0.3 mm, number of holes 20,000)

On the other hand, if a pulsed electron beam of 100 kV, 30 mA, is used, the time needed to drill a through-hole is 0.02 ms, so that 5,000 through-holes can be drilled every second. Although the beam deflection time of several microseconds or less is ignorable, the deflection area limitation must be taken into account. If the deflection area is 40 mm x 40 mm, about 1,000 through-holes can be drilled in the area, and will be drilled in 0.2 second using a pulsed electron beam. However, since it takes more than 1 second to prepare the next area for drilling by numerical control, the total time required to complete the work on one area is about 1.5 seconds. Since a PC board of the foregoing dimensions can comprise 80 deflection areas and automatic PC board loading also takes some time, the time required to complete the drilling of one PC board will be over 2 minutes.

Pulsed electron beam drilling offers more advantages. For example, it enables finer holes to be drilled, requires virtually no tools subject to wear to be used, and can be applied to any type of material.

4.2 Metal Drilling

Since metals such as stainless steel, titanium, molybdenum, and tungsten are hard and stiff, it used to take a lot of time to machine them and it was impossible to drill microholes in them. The use of the pulsed electron beam technique makes it possible to drill holes of high aspect ratios (ratios of hole depths to hole diameters) in such metals at high speed without involving any possibility of tool wear or breakage.

In pulsed electron beam working, when the target material is irradiated with a beam, it starts boiling, causing a cavity called a beam hole to be formed. The beam energy is then led into the material interior via the beam hole to proceed with the working. The speed at which the beam hole advances deeper into the material being worked on is closely related to the beam power density. Figure 9 shows the relationship between the time required for a beam to penetrate an 0.2-mm thick stainless steel plate (penetration time) and the beam power density. As it shows, the higher the beam power density, the shorter the penetration time.

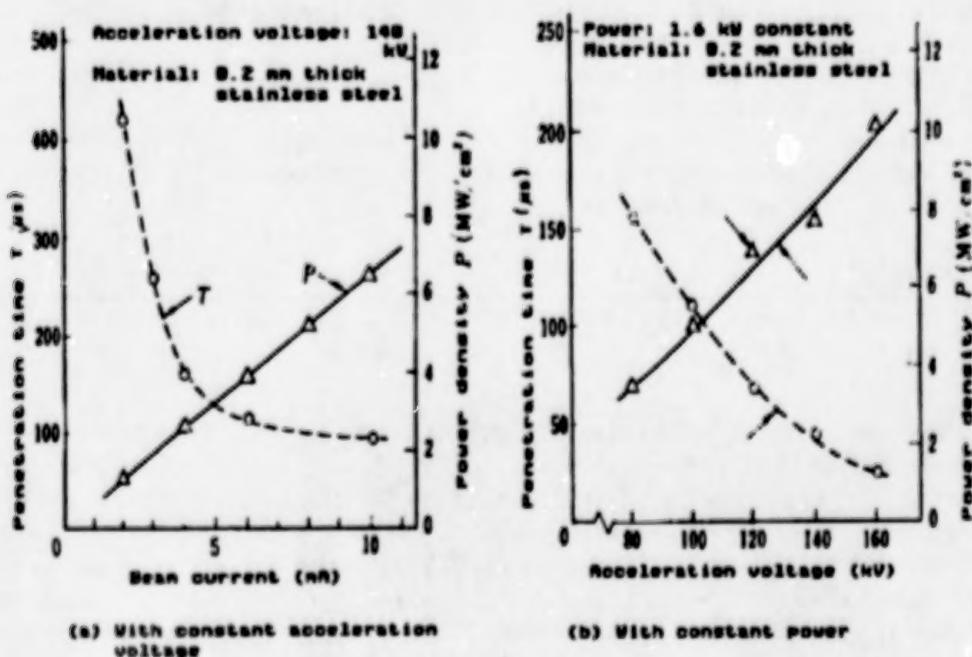


Figure 9. Beam Penetration of Time Vs. Power Density

Examples of microholes drilled in SUS304 stainless steel using pulsed beams are shown in Photo 2 [not reproduced]. Whereas the 0.1-mm thick plate is penetrated when it is irradiated with one 0.2-ms pulse of a beam of 100 kV, 30 mA, the 6-mm thick plate must be irradiated with two pulses of 140 kV, 40 mA (total irradiation time: 15 ms) before it is penetrated. The through-holes drilled in thicker plates have higher aspect ratios. The through-holes drilled in the 12-mm thick plate have an 0.5-mm diameter on the beam inlet side and an 0.2-mm diameter on the beam outlet side. Such through-holes may be usable in microfilters for brewing.

Through-holes with an 0.2-mm diameter drilled in an 0.4-mm thick plate of molybdenum, a metal which is difficult to machine, are shown in Photo 3 [not reproduced]. It took 1.5 ms for each to be completely drilled. Microholes drilled through a titanium alloy plate meant to be a material for laminar flow control-type wings are shown in Photo 4 [not reproduced]. The holes drilled by irradiating the plate with a beam of 120 kV, 10 mA, for 0.4 ms have a diameter of 0.1 mm (± 0.1 mm) and are spaced at 0.7 mm intervals. The ability of pulsed electron beams to instantaneously drill microholes can be fully displayed in this type of application in which many microholes are to be drilled.

4.3 Metal Engraving

Electron beams can also be used for metal engraving. In electron beam metal engraving, an electron beam is emitted onto the target metal surface to remove a very small amount of material by fusion or evaporation.

Photo 5 shows an example of electron beam application for metal engraving. In the application, an electron beam is used to engrave fine dents on the surface of a roller (dulling), and the steel plates rolled out by rollers with dulled surfaces have improved paintability due to the fine rugged patterns impressed on their surfaces. Compared with conventional dulling processes, such as the electric spark method and the shot blast method, the electron beam method enables the surface roughness and density to be controlled as desired, contributing to the production of steel plates whose surfaces can be painted with high clarity.

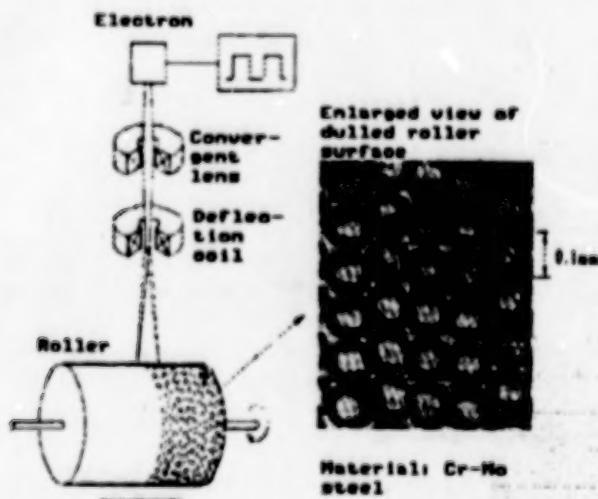


Photo 5. Roller Surface Drilling

4.4 Precision Welding

In pulsed electron beam welding, the output power can be controlled quite precisely by controlling the number of pulses to be emitted, and the average amount of heat input to the workpiece can be held at a minimum by controlling the amount of energy per pulse. Pulsed electron beam welding,

therefore, facilitates weld zones, which have not been very strained or affected by heat, to be obtained.

In Photo 6, sectional views of two beads, one generated by applying a continuous electron beam and the other by applying a pulsed electron beam, are compared. The two beams applied are both of a constant average amount of input heat per unit time. As the photo shows, the bead formed by applying a continuous beam is relatively shallow and is shaped like a wine glass, whereas the one formed by applying a pulsed beam is deep and has a highly linear shape. These differences between the two beads are thought to be attributable to the fact that the pulsed beam has a smaller effective diameter than the continuous beam.

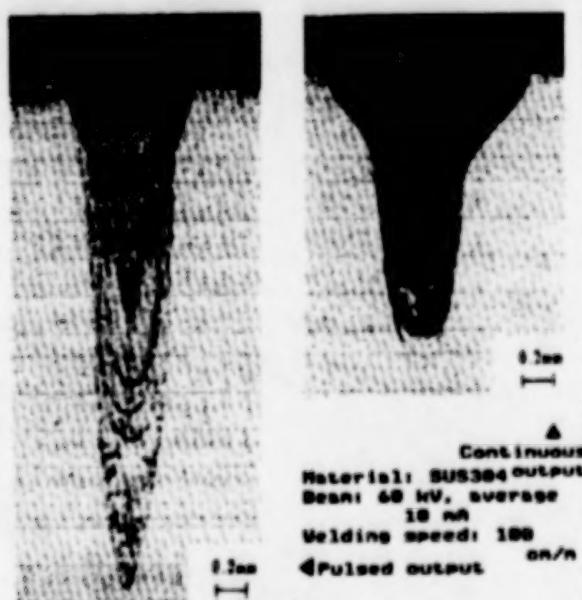


Photo 6. Beads Formed by Pulsed Electron Beam Welding

5. Conclusion

The concept of pulsed electron beam working, specifically, drilling, an outline of the authors' technique for such working, and examples of applications of the technique have been described. The technique may soon be put to use for PC board drilling and other applications and it may possibly contribute toward innovating various manufacturing processes.

The important targets to be achieved in the future utilizing this technique include developing measures to prevent the electron beam from being scattered by vapor and to prevent the vaporized material from being redeposited over the area around the point of working. With regard to the hardware needed to practice this technique, it is considered necessary to develop electron gun systems which can converge beams into smaller spots than presently possible in order to meet the needs for increasingly fine fabrication processes.

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